AD-A163 603

DAAK70-79-C-0249

(12)

DEVELOPMENT OF 3 AND 5KW FUEL CELL POWER PLANTS

S. ABENS AND M. FAROOQUE
ENERGY RESEARCH CORPORATION
3 GREAT PASTURE ROAD
DANBURY, CT 06810

12 DECEMBER 1985

FINAL TECHNICAL REPORT

FOR PERIOD OCTOBER 1979 TO JULY 1985

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

PREPARED FOR:

BELVOIR RESEARCH DEVELOPMENT AND
ENGINEERING CENTER
DIRECTORATE FOR LOGISTIC SUPPORT
STRBE-F
FORT BELVOIR, VA 22060-5606

CONTRACT DAAK70-79-C-0249

NOTICES

Disclaimers

Disposition

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DAAK70-79-C-0249	2. GOVT ACCESSION NO. AD-A163	3. RECIPIENT'S CATALOG NUMBER 603
4. TITLE (and Subtitle) Development of 3 and 5kW Fuel Cell Power Plants		5. TYPE OF REPORT & PERIOD COVERED Final Report October 1979 - July 1985
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) S. Abens and M. Farooque		8. CONTRACT OR GRANT NUMBER(s) DAAK70-79-C-0249
9. PERFORMING ORGANIZATION NAME AND ADDRESS Energy Research Corporation 3 Great Pasture Road Danbury, CT 06810		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1V463702DG1103
11. CONTROLLING OFFICE NAME AND ADDRESS DCAS Management Area, Bridgeport 550 South Main Bridgeport, CT 06497		12. REPORT DATE 17 December 1985
		13. NUMBER OF PAGES 114
14. MONITORING AGENCY NAME & ADDRESS(If different from Controlling Office) Belvoir Research Development and Engineering Center Directorate for Logistic Support STRBE-F Fort Belvoir, VA 22060-5606		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

This document has been approved for public release and sale; its distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for public release, distribution unlimited.

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fuel Cell Power Plant; Premixed Methanol Fuel; Phosphoric Acid Fuel Cell; 3 and 5kW Power Plants; Methanol Reforming; Fuel Cell Power Conditioning; Neat Methanol Fuel; Water Reclamation from Fuel Cell.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Phosphoric acid fuel cell power plants for use as tactical utility power sources have been developed. The power plants operate on 58% methanol-42%water fuel. Two fully automatic 3kW units were built, tested, and delivered to U.S. Army Belvoir R&D Center. Thermal efficiency was 23% with AC and 26% with DC output.

A brassboard 3kW power plant operating on neat methanol was also constructed, tested, and delivered to the Army.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

EXECUTIVE SUMMARY

This report summarizes the efforts under a U.S. Army Troop Support Commands' Ft. Belvoir Research & Development Center (Ft. Belvoir, VA) sponsored program for the development of fully automatic 3 and 5kW fuel cell units for use by the Army as tactical utility power sources. methanol, a non-petroleum fuel which is produced from a variety of sources (natural gas, coal, wood and waste materials), has been chosen as fuel for this power source. As a part of this project, designs were developed for both 3 and 5kW premixed fuel units, and two 3kW units were constructed, tested and delivered. Also, the design of a 3kW neat methanol unit based on water reclamation was developed and a brassboard unit was constructed, tested and delivered.

The methanol-water premix fuel cell power plant operates on a 1:1.3 molar mixture of methanol and water (approximately 58 wt% methanol and 42 wt% water), which is converted in a steam reformer, operating at 300°C, to hydrogen-rich product gas. The fuel cell uses 60 to 65% of the hydrogen to produce DC electricity, and the balance is combusted in a burner to supply heat required for the endothermic reforming process. The phosphoric acid fuel cell stack is air-cooled and operates at a temperature of 190°C.

The fuel cell power plant is capable of delivering either regulated DC or AC electrical power through the use of interchangeable power conditioners. A microprocessor based controller provides event sequencing and system control during startup, shutdown and operation of the power plant.

The 3kW power plant operation was tested from idle to maximum power output for both AC and DC versions. For a power plant output of 3 kW DC, the stack produced about 3.9 kW of which about 570 and 330 watts were spent for the ancillary components power and the power conditioner, respectively. Consumption of the mixed methanol-water fuel varied from 2.4 liters/hr at idle to 4.0 liters/hour at full power. At the rated power of 3 kW DC, neat methanol (undiluted) consumption was 0.68 kg/kWhr which corresponds to an overall power plant thermal efficiency of 26% based on the lower heating value of methanol. Overall thermal efficiency for full load AC operation was 23% (LHV).

The automatic starts required less than 15 minutes at room temperature and less than 3 minutes if restarted immediately after shutdown. Liquid fuel consumption for room temperature startup was approximately 1200 gm of premixed fuel. Also, about 90 Whr of electrical output supplied from the onboard 24V Ni-Cd battery was required for room temperature starts.

An improvement in fuel volume, weight and supply logistics was demonstrated by operating a fully automatic brassboard power plant on neat (undiluted) methanol fuel, based on on-board water reclamation and the methanol-water mixing concept.

This program has successfully demonstrated that both premixed and neat methanol power units are viable alternatives to conventional gensets for mobile power generation applications.

LIST OF CONTRIBUTORS

S. Abens

B. Baker

M. Farooque

R. Hayes

J. Hofbauer

W. Keil

P. Marchetti

T. Schneider

P. Voyentzie

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

TABLE OF CONTENTS
(concluded)

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF FIGURES
(concluded)

LIST OF TABLES

1.0 INTRODUCTION

This report describes design, construction and test results obtained on a program for the development of 3 and 5kW fuel cell power plants for the U.S. Army. The Army's performance goals for these power plants are summarized in Table 1.1.

The U.S. Army fuel cell program is intended to meet the requirements set forth in the Required Operational Capabilities Document for "Silent Lightweight Electric Energy Plants" (SLEEP). This is an effort to provide the Army with a capability that is not met by the current inventory of gasoline and diesel engine driven generator sets. The engine driven sets do not meet the requirements for reliability, noise, and infrared suppression that are deemed necessary to operate successfully in the highly complex battlefield of the future.

Methanol is the fuel of choice based on the ease with which it can be converted to hydrogen in a steam reformer as well as its ready availability, and ease of storage and transportation. In addition, the use of methanol as a fuel supports the goals of the Army Energy Office to reduce the dependence on petroleum fuels by developing equipment that will utilize alternate and/or synthetic fuels [1]. Methanol may become the product of the synthetic fuel conversion techniques based on coal, and is one of the leading fuels which is envisioned to displace current petroleum fuels.

The program was originally organized in five major tasks: (1) Design Development, (2) 3kW Brassboard Power Plant, (3) 5kW Brassboard Power Plant, (4) 3kW Prototype Power Plant Development and (5) 5kW Prototype Power Plant Development. Two other tasks were added: (6) Separated Air Cooled (SAC) Stack Development and (7) Neat Methanol Power Plant Development. The 5kW brassboard and prototype power plants were not constructed.

Under the design development task, conceptual designs were developed for both a 3 kW and a 5kW plant, with emphasis on

TABLE 1.1

SPECIFICATIONS FOR 3/5kW FUEL CELL POWER PLANTS

OUTPUT VOLTAGE	
MODE II/III	120/240/208 VAC, 60/400 Hz, 1/3 Φ
MODE IV	28 VDC
FUEL	58 wt% Methanol - 48 wt% Water
FUEL CONSUMPTION	0.82 kg MEOH/kWhr (1.8 lb/kWhr)
NOISE LEVEL	Inaudible at 100 meters (328 ft)
STARTUP TIME	15 minutes
WEIGHT	45 kg/kW (100 lb/kW)
VOLUME	0.11 m^3/kW (4 ft^3/kW)
MTBF	750 hours
LIFE	6,000 hours/2,000 starts

interchangeability of components. The system and control concepts were verified by constructing and operating a 3kW brassboard power plant. A number of design modifications evolved as a result of the experience gained with this power plant.

A major task of the program consisted of construction and testing of two 3kW prototype power plants. These power plants were delivered to the U.S. Army Troop Support Commands' Belvoir R&D Center. A photograph of one of these units is shown in Figure 1.1. A description of components used in this power plant is available in Appendix A.

Finally, a neat methanol fuel cell power plant system based on product water reclaim was developed. A brassboard power plant was constructed, tested and delivered.

Sections 2 and 3 of this report descri e the design of the 3 and 5kW power plants. Performance of the 3kW prototype power plant is described in Section 4. Component development and testing conducted with the 3kW brassboard power plant are described in Sections 5 and 6. The neat methanol power plant development efforts are reported in Section 7. Appendix C describes abbreviations, definitions and equations pertinent to this report.

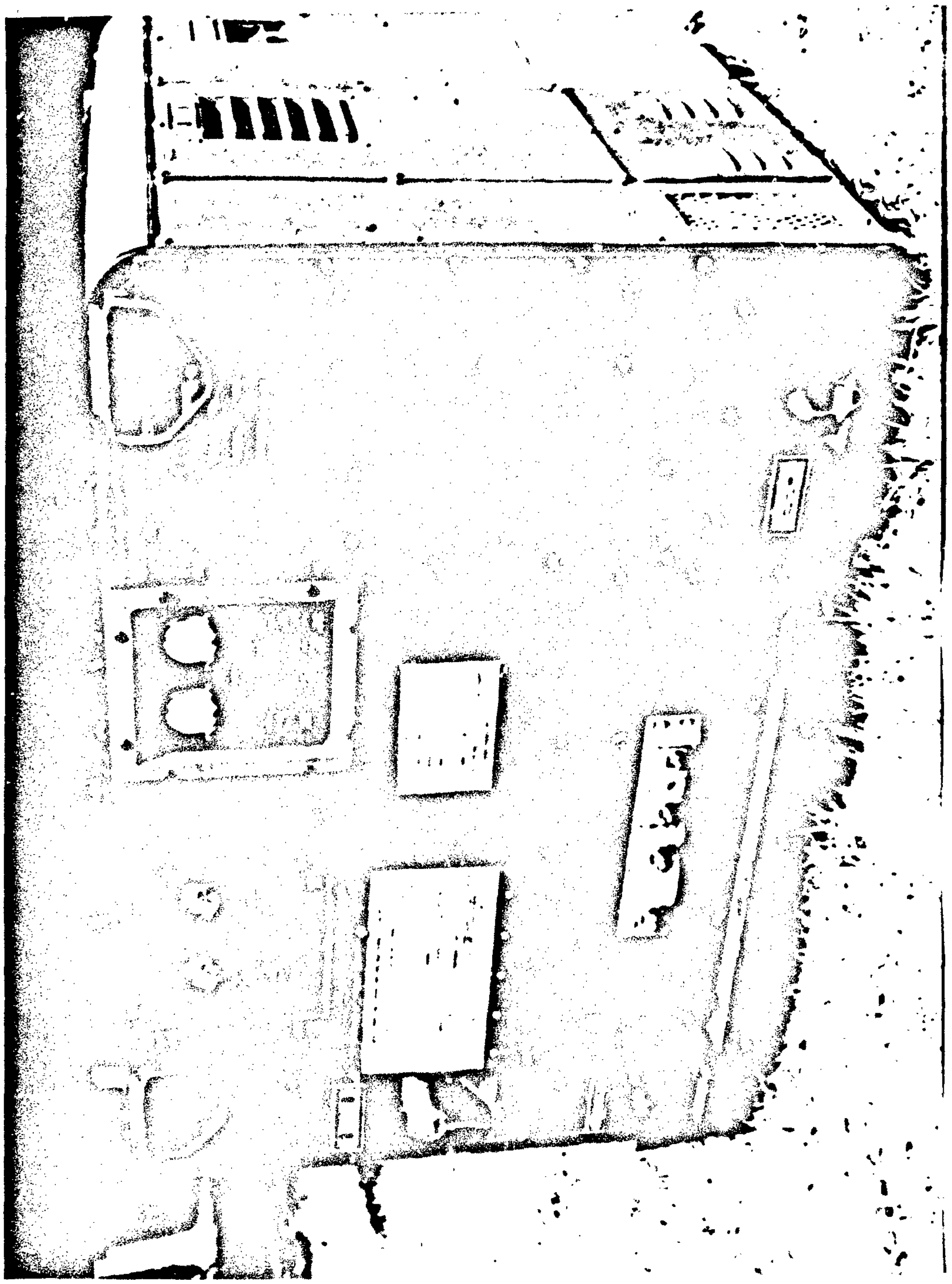


FIGURE 1.1
3kW AC POWER PLANT

2.0 GENERAL DESCRIPTION OF THE 3/5kW POWER PLANT

2.1 DESIGN CONCEPT

The fully automatic methanol fuel cell power plant developed for the U.S. Army is based on the use of a steam reformer with a phosphoric acid fuel cell stack. The power plant system concept is shown in Figure 2.1. Liquid fuel (58 wt% methanol and 42 wt% water) is fed to the reformer. The reformer generates hydrogen which, together with water vapor and byproduct carbon dioxide flows to the fuel cell stack. About two thirds of the hydrogen is converted to unregulated DC electricity in the stack. The residual hydrogen is combusted in the reformer burner and supplies the heat required for vaporization and steam reforming. Ambient air is used as the cathode reactant and as the cooling medium for the fuel cell stack. The power plant can be equipped with either a DC voltage regulator or an inverter giving AC output. The two power conditioners are interchangeable.

For organizational purposes, the fuel cell power plant is subdivided into six subsystems:

Fuel Cell
Fuel Conditioning
Electrical
Control
Power Conditioning
Structural

The interaction between the various functional subsystems is shown in Figure 2.2. Figure 2.3 provides a functional schematic of the fuel conditioning and fuel cell subsystems, and the key ancillary components needed for operation of the power plant. Source data and functional information of all power plant components is available in Appendix A.

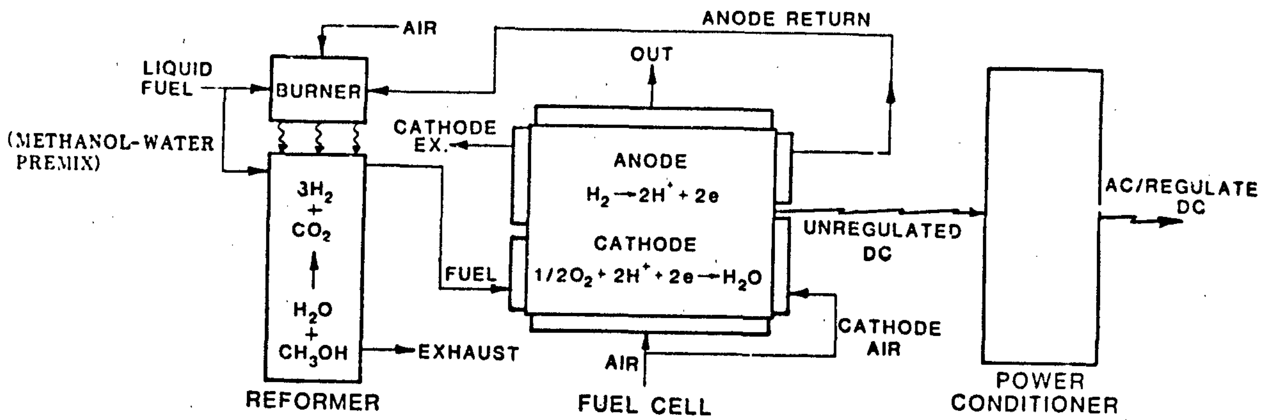


FIGURE 2.1

FUEL CELL POWER PLANT CONCEPT

SD0169

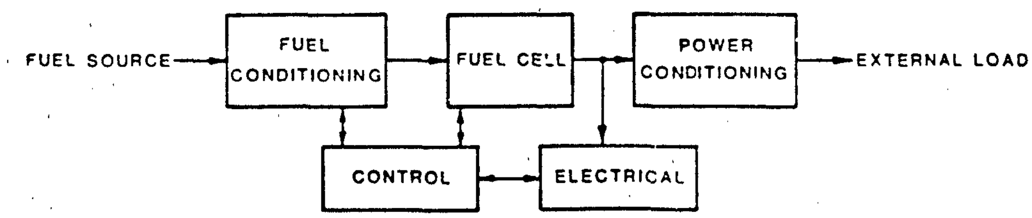


FIGURE 2.2

FUEL CELL POWER UNIT -
FUNCTIONAL SUBSYSTEMS BLOCK DIAGRAM

SD0152

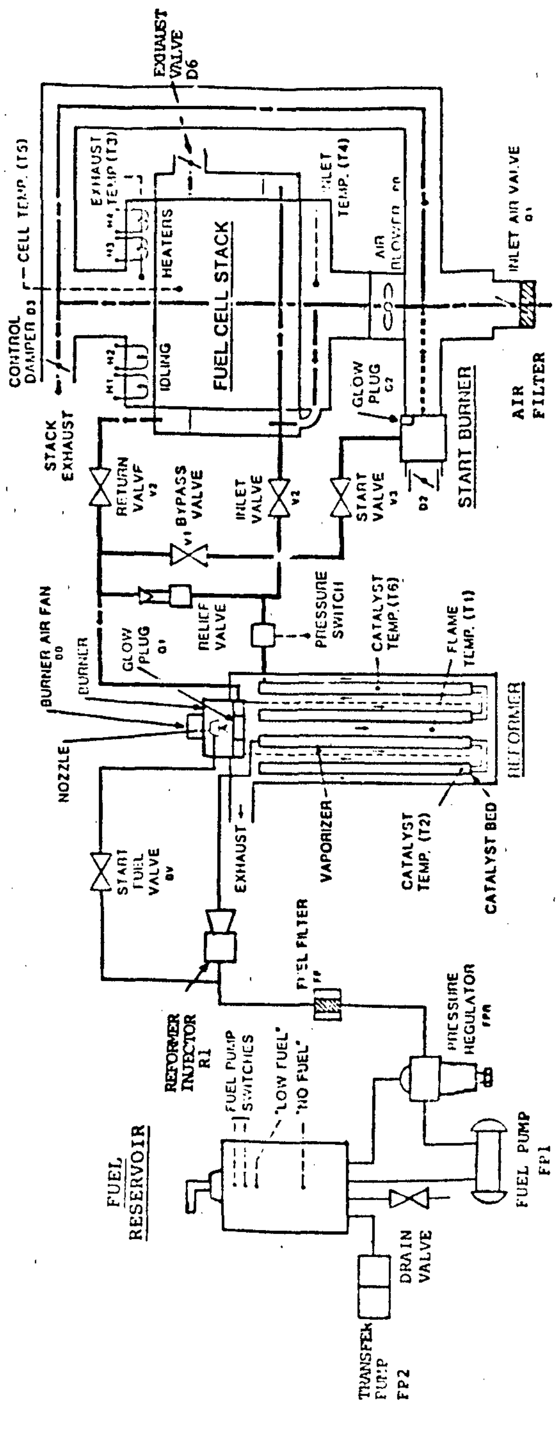


FIGURE 2.3

3/5kW FC POWER PLANT FUNCTIONAL SCHEMATIC

SD0121A

2.2 CONNECTIONS AND CONTROLS

Location of external connectors and controls for the power plant is shown in Figure 2.4. The Ground Connector at the lower left is for an electrical ground rod. The Auxillary Startup Power Connector is for connecting an external battery or other power source in case of low output from the internal battery. This connector will accept the mating plug on a standard military power supply jumper cable. The External Fuel Connection located on the front lower right-hand side of the power unit is for attaching a hose that will carry the fuel in from an external supply.

The Main Control Panel contains the switches, meters, and indicators required to control operation of the power plant.

The Power Conditioner Control Panel contains the switches, meters and indicators required to control the power conditioner. Two interchangeable panels, one for use with an AC power conditioner, the other for use with a DC power conditioner, are available for use with the power plant.

2.3 OPERATION

The power plant control panel is shown in Figure 2.5. The START/OFF switch allows the operator to start/shutdown the power unit.

The power plant control actuators respond to operator action and signals from sensors within the system. The condition of the actuators is dependent on the operating mode, as shown in Table 2.1.

The power plant has three distinct modes of operation:

1. Standby (Startup)
2. Ready (Run)
3. Shutdown

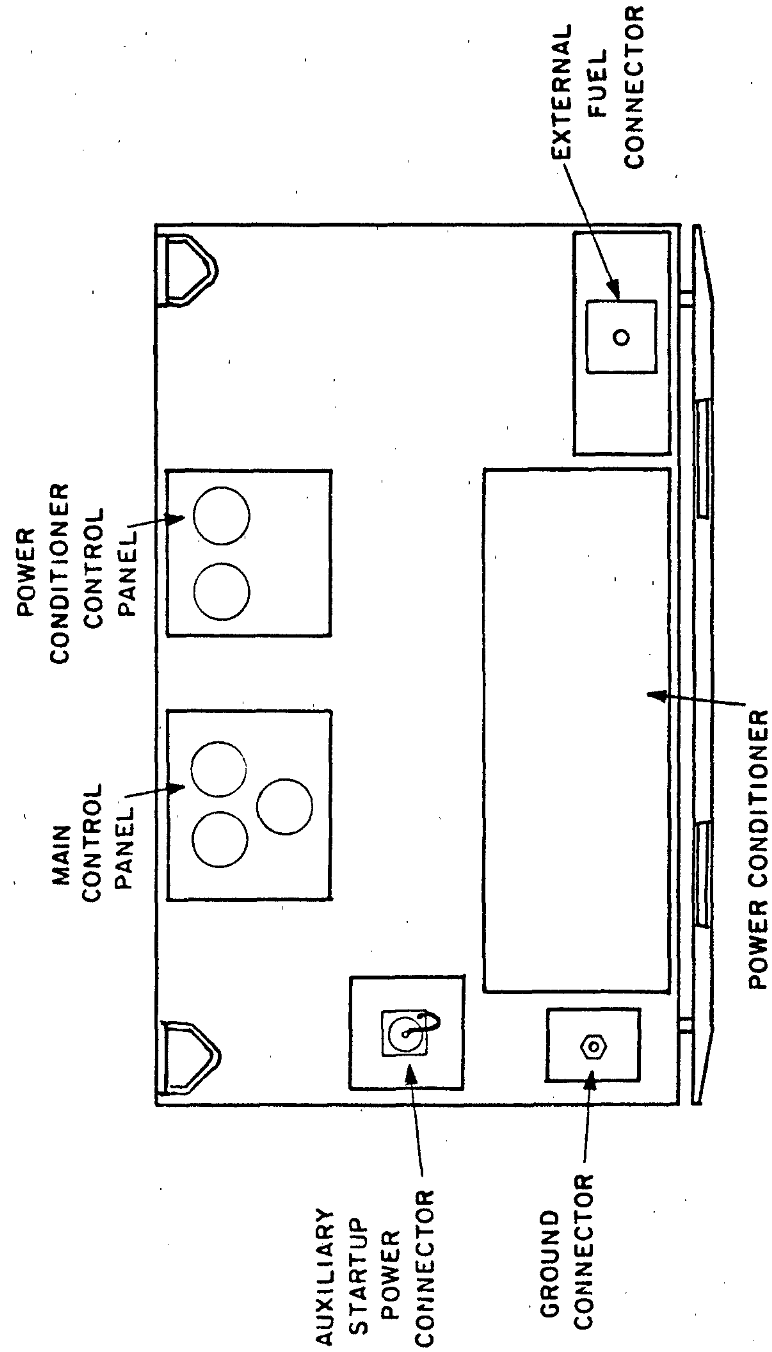


FIGURE 2.4
3/5kW FUEL CELL POWER UNIT - FRONT VIEW

SD0118

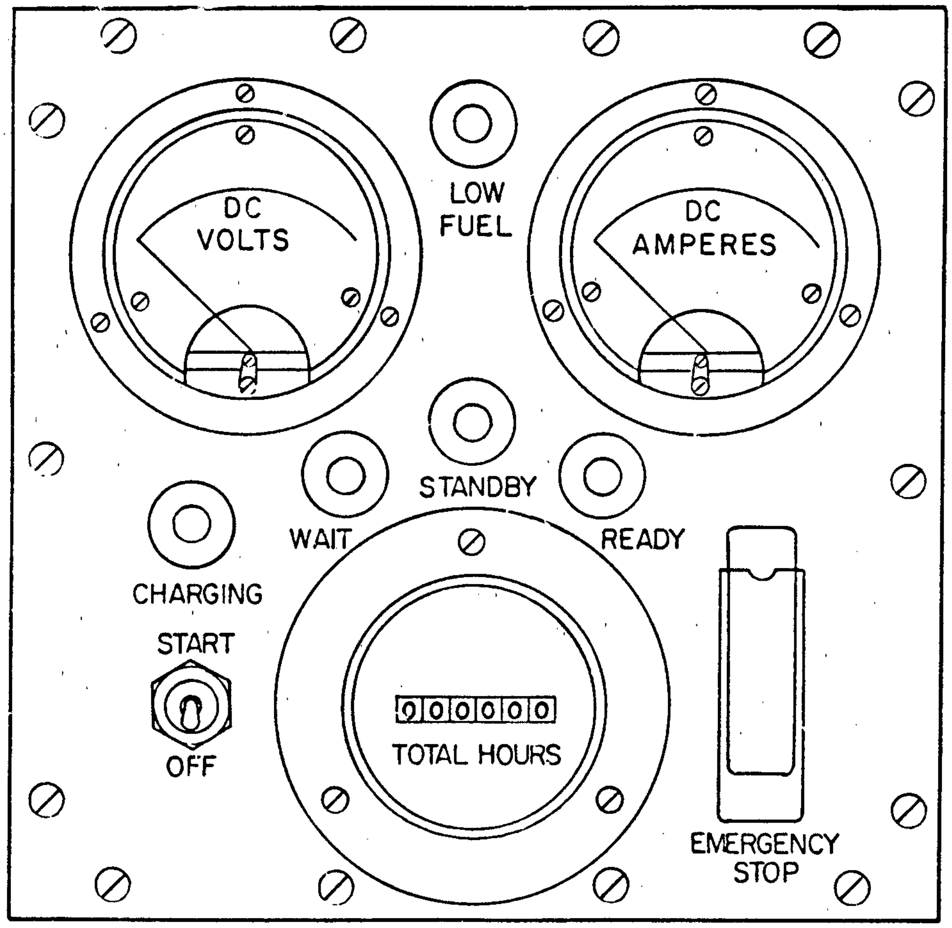


FIGURE 2.5
POWER PLANT CONTROL PANEL

SD0111

TABLE 2.1

METHANOL POWER PLANT CONTROL ACTUATORS

	STANDBY		READY (RUN)	SHUTDOWN (MANUAL OR SYSTEM)		EMERG. STOP
	FIRST 4-5 Min.	SECOND PERIOD		FIRST ACTION	SECOND ACTION	
Start Fuel Valve, BV	Open	Open	Closed	Closed	Closed	Closed
Bypass Valve, V1	Open	Closed	Closed	Open	Closed	Closed
Inlet/Return Valve, V2	Closed	Closed	Open	As Is	Closed	Closed
Start Burner Valve, V3	Closed	Open	Closed	As Is	Closed	Closed
Inlet Air Damper, D1	Closed	Closed	Open	Open	Closed	Closed
Start Burner Damper, D2	Closed	Open	Closed	As Is	Closed	Closed
Control Damper, D3	Closed	Open	Variable	As Is	Closed	As Is
Exhaust Damper, D6	Closed	Closed	Open	Open	Closed	Closed
Burner Blower, BB	Controlled	Controlled	Controlled	Full Speed	Off	Off
Air-Blower, PB	Off	On	On	As Is	Off	Off
Idling Heaters	Off	Off	Controlled	Off	Off	Off
Output Relay, K1	Off	Off	On	Off	Off	Off
Battery Relay, K2	On	On	Off	On	Off	Off
Parasitic Relay, K3	Off	Off	On	Off	Off	Off

Startup of the power plant is initiated by momentarily moving the main control panel START/OFF switch to the START position. This closes the battery relay (K2), powering the 24 VDC bus. Simultaneously, the micro-processor is initialized and the STANDBY indicator lamp on the panel lit to indicate that startup is in progress. The 24 VDC to 115 VAC 400 Hz inverter, bypass valve (V1), the high pressure fuel pump (FP1), and the glow plug (G1) are energized. The burner blower (BB) runs at low speed for one minute, the start fuel valve (BV) is opened, and the burner blower speed is increased to provide air for combustion. When ignition is indicated by the flame temperature sensor (T1), the burner glow plug is turned off and the start burner glow plug (G2) is turned on. A shutdown is triggered if T1 does not sense ignition within one minute.

After the burner has run for one minute (longer for a cold start) the liquid fuel is turned on by the reformer injector (RI). The reformer product is returned to the reformer burner to provide fast heatup. When the catalyst temperature sensor (T2) indicates that the reformer is up to temperature, the stack air blower is energized and the control damper (D3) is opened. The fuel cell stack temperature sensor (T5) and the reformer catalyst bed temperature sensor (T6) determine subsystem temperatures. If heating is required, the start fuel valve (V3) is opened, the bypass valve (V1) is closed, and ignition occurs in the startup burner. If the flame temperature sensor (T4) does not indicate ignition in 20 seconds, shutdown is initiated. If the startup is attempted with a warm power plant (shortly after a shutdown), startup burner operation is bypassed.

When the fuel cell stack and the reformer are at operating temperature, the stack fuel valve (V2) is opened, the start valve (V3) is closed, the startup damper (D2) is closed, and the fresh air (D1) and cathode (D6) dampers are opened. A delay of ten seconds is allowed before closing burner valve (BV) to ensure presence of hydrogen-rich fuel in the stack and the burner. The fuel cell stack now assumes the idle heater load.

Control of stack temperature is accomplished by modulation of damper (D3) position (uses cooling air out temperature (T3) as the feed back input), the burner blower (BB) speed by stack current, and the reformer fuel flow rate by stack current (LS) and reformer temperature (T2).

The parasitic relay (K3) is energized and the battery relay (K2) is de-energized. The battery starts charging and the CHARGE light is turned on. At this point, the fuel cell stack supplies the heater, parasitic and the charging loads. The output relay (K1) is energized, STANDBY lamp goes off and the READY light comes on, indicating that the unit is ready to supply power to the load.

As the load current increases, the internal stack heaters are progressively disconnected.

Normal automatic shutdown cycle is initiated by moving the START/OFF switch to its OFF position. The battery relay is energized to supply power to components, the WAIT lamp is turned on, and the parasitic relay is de-energized. Actuator actions are sequenced as shown in Table 2.1. At the conclusion of the shutdown cycle, all components are in closed position, and relay K2 drops out, cutting all system power.

Shutdown also occurs automatically if the fuel is exhausted or any of a number of sensors indicate off-design condition in the power plant. Emergency stop is triggered by moving the EMERGENCY STOP switch to STOP position. Battery relay is immediately de-energized, thus cutting off all system power. This action also transfers the emergency 24 VDC line from housekeeping power to battery power, so that dampers D1, D2, and D6 will be returned automatically to their fully closed positions. Control damper D3, however, must be returned to its closed position by the operator (after emergency stop only).

THIS PAGE INTENTIONALLY LEFT BLANK

3.0 SUBSYSTEM DESIGN

3.1 FUEL CELL

The fuel cell subsystem is comprised of a fuel cell stack, an air blower, control elements, and associated sensors. The 3 and 5kW power plants use separate air-cooled stack designs and identical sensors and control elements. However, the stack and blower sizes are different.

The design features of the fuel cell subsystem are summarized in Table 3.1. A photograph of the 3kW fuel cell stack with gas manifolds and valves is shown in Figure 3.1.

Assembly of the 3kW stack is shown in Figure 3.2. The stack contains separate flow paths for conditioned fuel, process air, and cooling air. The gases are distributed through the stack by means of three sets of manifolds. Fuel and process air flow co-current in the long direction of the cell. Air for cooling flows through channels running in the short direction of every fifth bipolar plate. Cooling air is recirculated to the inlet side of the blower in order to raise the incoming air temperature to about 130°C. The stack is designed to operate with a cooling air temperature rise of 55°C.

The power generating unit in the 3kW power plant is an air-cooled 80-cell phosphoric acid fuel cell stack built with lightweight hardware. A photograph of the stack without manifolds is shown in Figure 3.3. Each repeating fuel cell element in this stack consists of a 0.3 mg/cm^2 Pt loaded anode, a porous matrix saturated with 30 ml of 102 wt% phosphoric acid, and a 0.5 mg/cm^2 Pt loaded cathode. A bipolar gas distribution plate having gas flow channels on both sides is shared by two adjacent cells. The fuel cell stack manifolds are made from aluminum and coated with PFA to provide protection from phosphoric acid attack and dielectric separation. The stack is equipped with tubes for acid addition.

TABLE 3.1

FUEL CELL SUBSYSTEM DESIGN SUMMARY
(Mid-life Values)

POWER PLANT RATING	3kW	5kW
Power Output, kW	4.2	7.2
Operating voltage, volts	43.0	43.4
Operating current, amps	97.5	166
Hydrogen Utilization, %	65	65
Methanol consumption, kg/hr (lb/hr)	2.4 (5.3)	3.8 (8.4)
Number of cells	80	75
Nominal cell size, cm x cm (in. x in.)	17.8 x 42 (7 x 16.5)	30 x 43 (12 x 17)
Active area, cm^2 (ft^2)	585 (0.63)	1050 (1.13)
Cooling air temperature rise °C (°F)	56 (100)	56 (100)
Cooling Air pressure drop, cm H_2O (in H_2O)	<2.0 (<0.8)	<2.0 (<0.8)
Cooling air blower output, g-mole/min (lb/hr)	225 (860)	325 (1250)
Idle heater capacity, watts	4 x 400	4 x 550

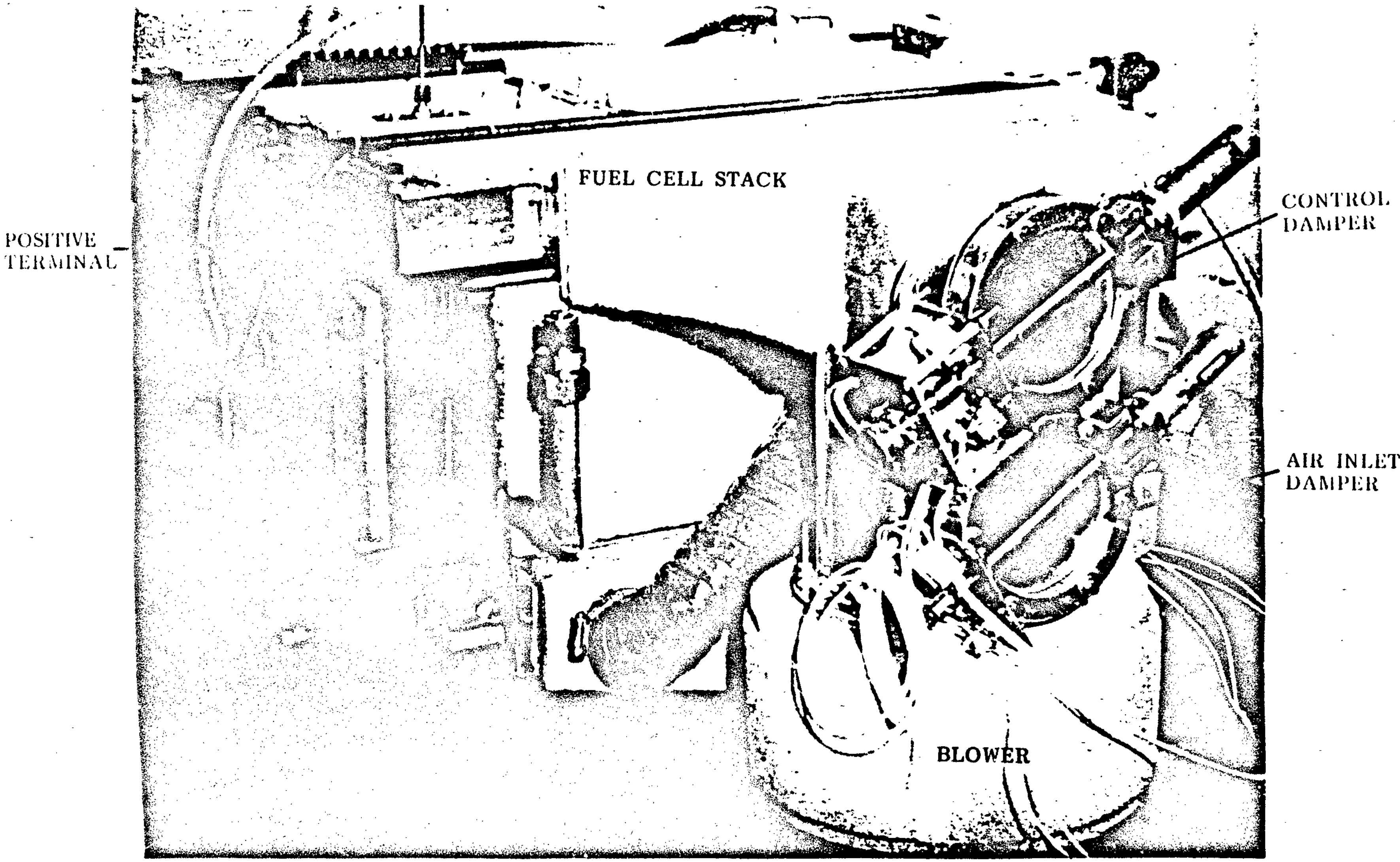


FIGURE 3.1. THE 3kW FUEL CELL SUBSYSTEM

SP0035

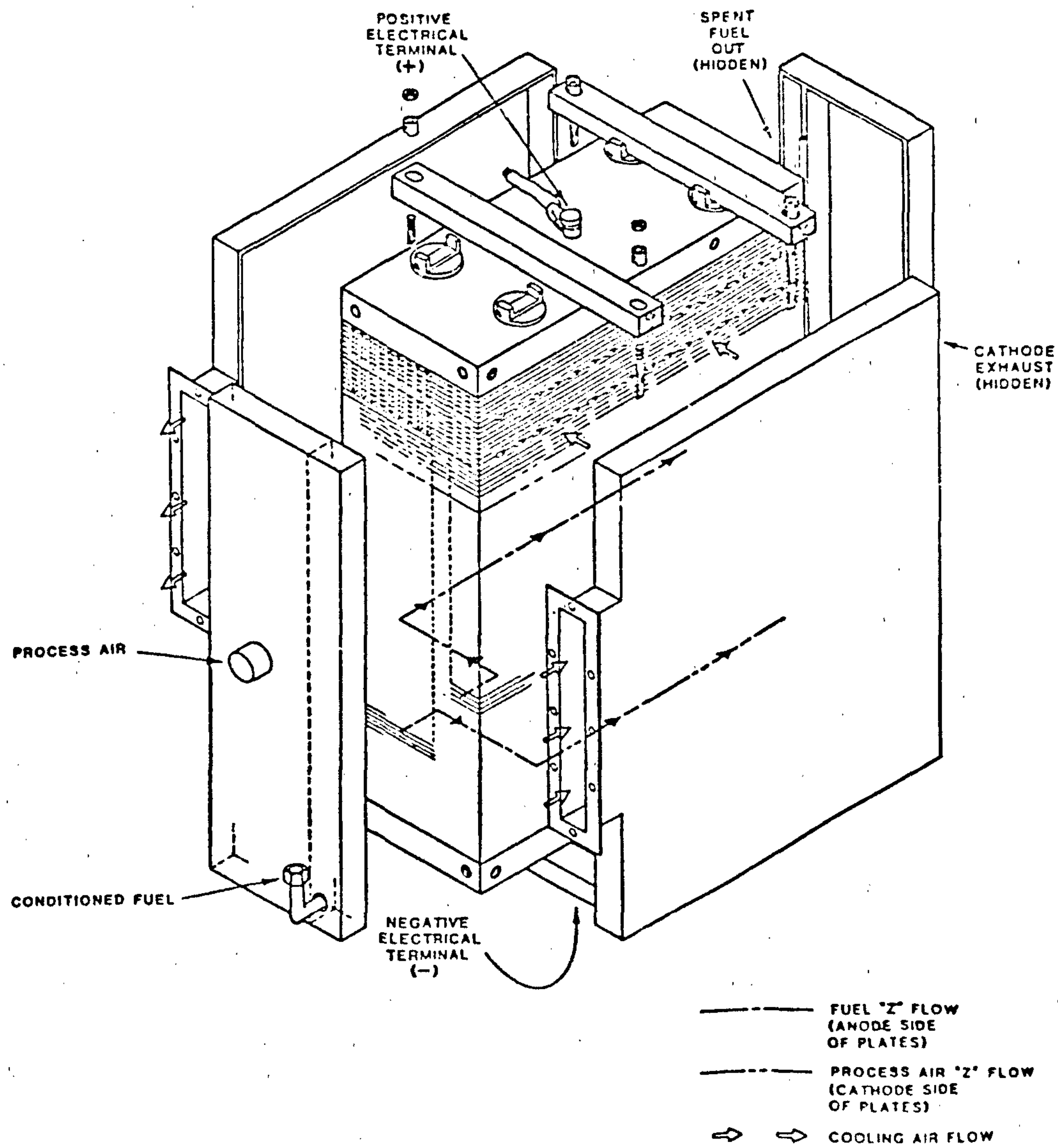


FIGURE 3.2
ASSEMBLY OF THE 3kW POWER PLANT STACK

SD0097R

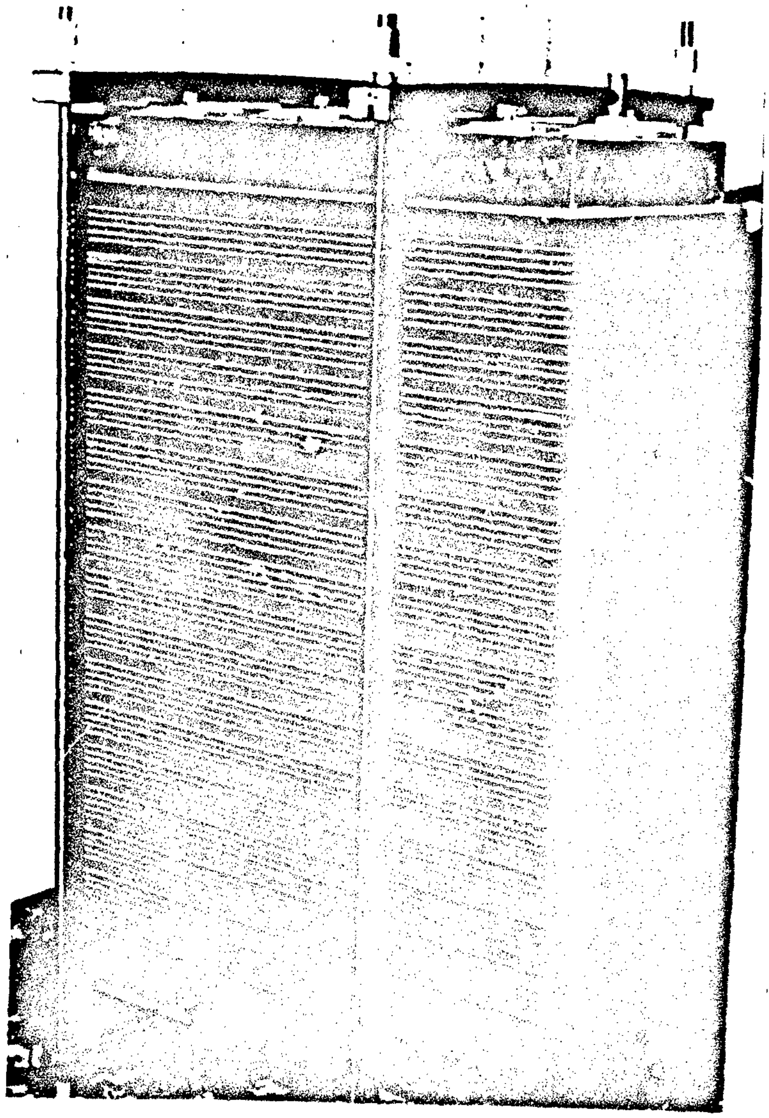


FIGURE 3.3. THE 3kW FUEL CELL STACK
(80-CELL)

The control damper regulates incoming air rates by controlling the rate of hot air exhaust in accordance with cooling requirements. The exhaust air temperature sensor output is used for controlling the stack temperature. Four resistance heaters located in the stack cooling air manifold are connected across the stack terminals at low ouput loads to maintain stack current and temperature. With a progressively increasing load, the heaters are gradually disconnected.

Performance of the 3 and 5kW stacks is shown in Figures 3.4a and 3.4b. The fuel cell subsystem also carries voltage and current sensors, and three RTD (T3, T4 and T5) sensors which provide input to the system microcomputer.

3.2 FUEL CONDITIONER

The fuel conditioner subsystem design, shown in Figure 3.5, is identical for both the 3 and 5kW power plants. The fuel conditioning subsystem comprises a liquid fuel delivery system, a reformer assembly and a startup burner.

3.2.1 Fuel System

A transfer pump (FP2) delivers fuel from the external source into the internal fuel reservoir which holds about a 15 minute fuel supply at 3kW, and a 10 minute fuel supply at 5kW output. Float actuated switches in the reservoir control the transfer pump to maintain the reservoir fuel level within preset limits. If the external fuel supply runs dry while the system is operating, the continuing drop in reservoir level actuates the "Low fuel" warning light switch to indicate that the internal fuel level is down to about 8 minutes supply for 3kW-power operation. The additional drop in fuel level actuates the "No fuel" switch to automatically shut down the power unit.

The main fuel pump (FP1) maintains a constant flow of fuel to the pressure regulator (FPR) which provides constant fuel

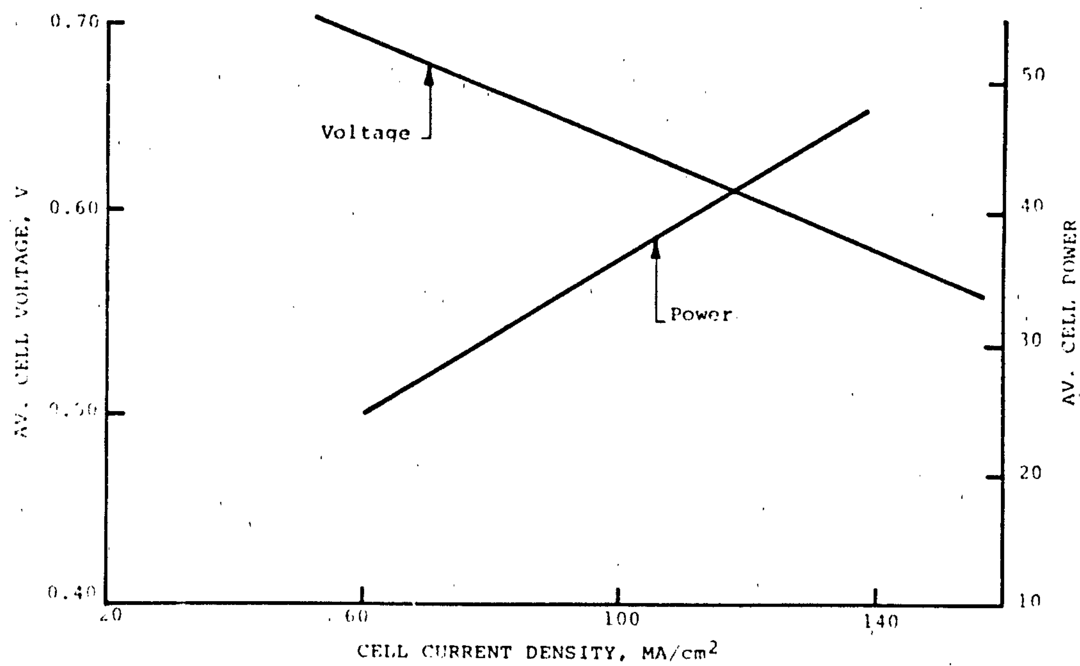


FIGURE 3.4a.

CHARACTERISTICS OF 80-CELL STACK FOR 3kW POWER PLANT

SD0203R

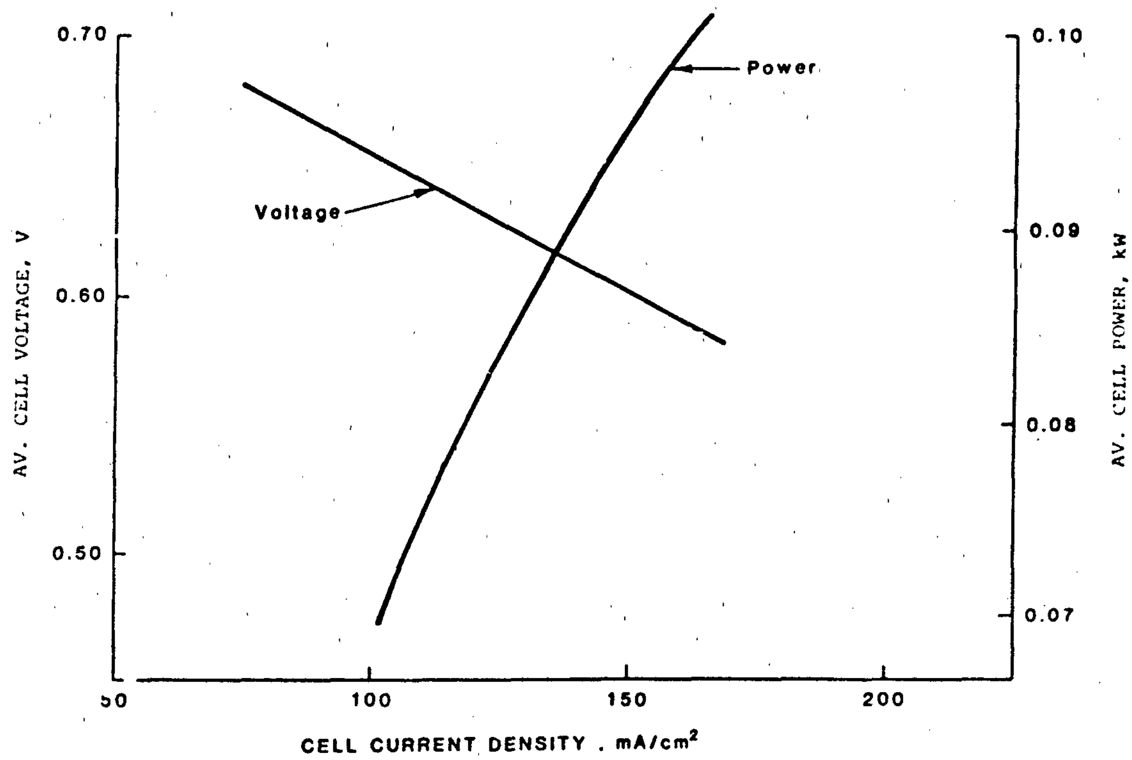


FIGURE 3.4b
PERFORMANCE OF 5-kW STACK (75-CELL)

SD0151PA

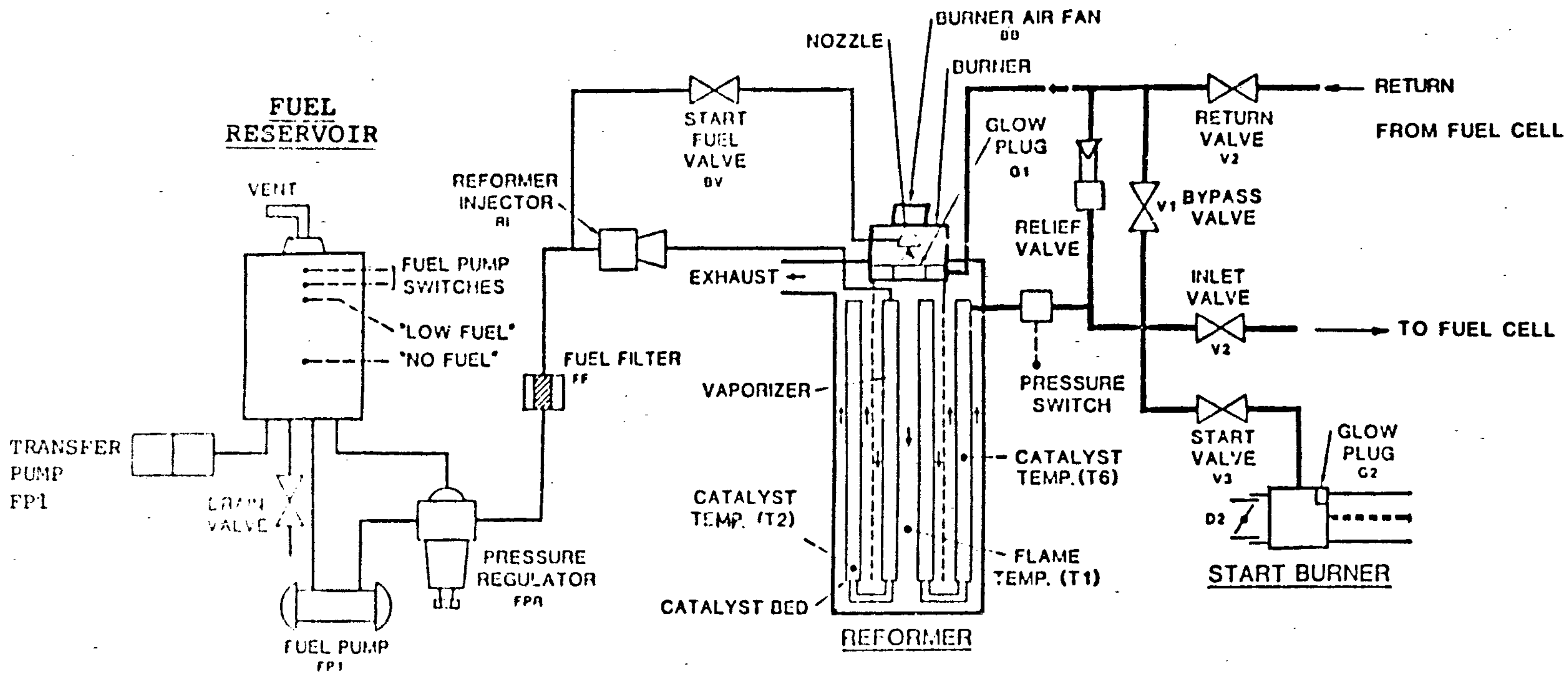


FIGURE 3.5

SCHEMATIC OF THE FUEL CONDITIONING SUBSYSTEM

SD0182R

pressure to the start fuel valve (3r) and the reformer injector (RI). The start fuel valve is open during startup to deliver liquid fuel to the reformer burner nozzle. The reformer injector is modulated in response to stack current and reformer temperature sensor outputs.

3.2.2 Reformer

The function of the reformer assembly is to convert liquid fuel into a gas mixture containing free hydrogen for fuel cell consumption. A photograph of a fully assembled 3kW reformer is shown in Figure 3.6. The principal elements of the reformer assembly are a catalyst bed, a vaporizer/superheater, a liquid fuel/hydrogen burner, and a burner air fan.

A cross-sectional sketch of a reformer assembly, shown in Figure 3.7, shows the location of the principal elements in the reformer assembly. The design incorporates an annular catalyst bed with a centrally located burner and vaporizer/superheater.

A commercial copper-zinc shift catalyst catalyzes both the water gas shift and the steam reforming reactions. The upflow bed design is based on a maximum product gas space velocity of $2700 hr^{-1}$, corresponding to a fuel processing rate of 85 gm/min. The reformer catalyst temperature ranges between 230 and 340°C depending upon fuel feed rate. Typical gas composition under these operating conditions is 74% H_2, 24.5% CO_2 and 1.5% CO on a dry basis.

The vaporizer/superheater design allows fast generation of superheated vapor fuel from the liquid fuel input. Liquid fuel flows downward through the vaporizer and is vaporized and superheated to approximately 450°C. A flame temperature sensor and two reformer temperature sensors provide input to the control subsystem microprocessor for controlling the reformer.

The burner is designed to burn liquid fuel from the fuel tank during startup and gaseous fuel from the stack exhaust during the

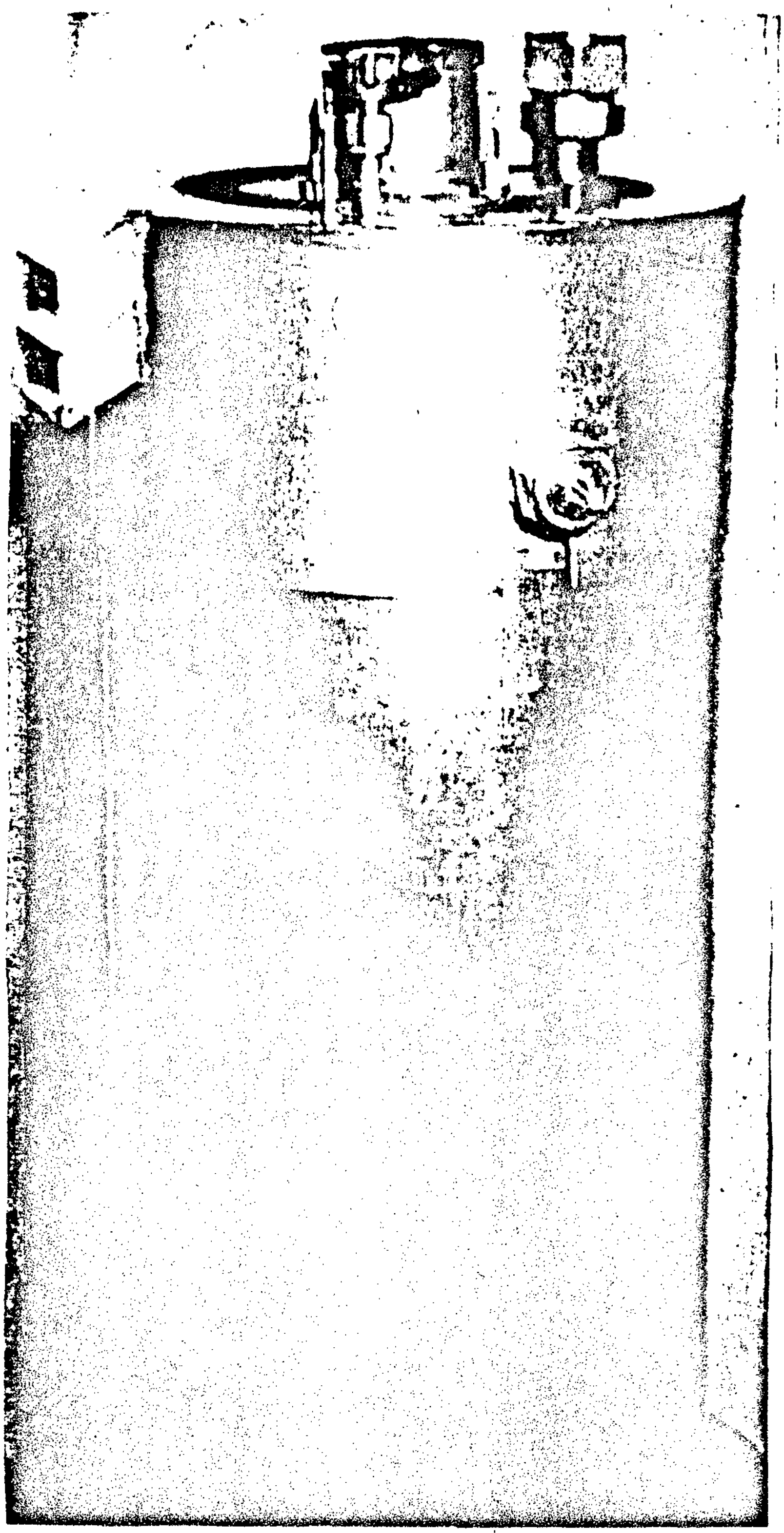


FIGURE 3.6 REFORMER ASSEMBLY

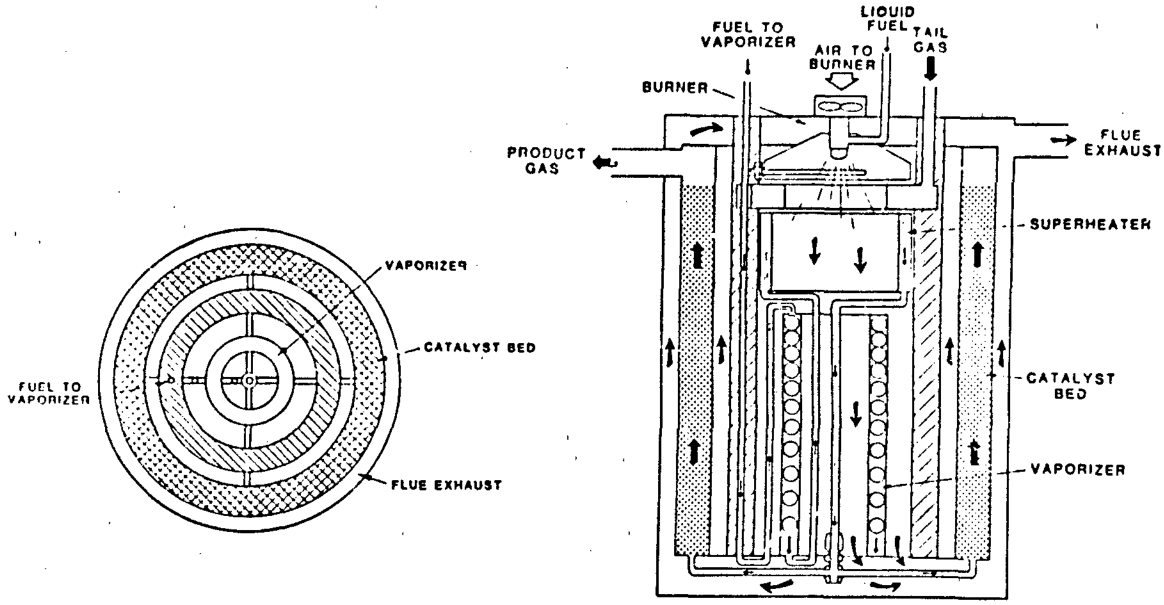


FIGURE 3.7

CROSS-SECTIONAL SKETCH OF THE REFORMER ASSEMBLY

SD0109

run mode. The variable speed air fan provides combustion air flow. The burner incorporates a platinized honeycomb disk below the combustion chamber to ensure complete combustion of the fuel.

The flow of reformate to the fuel cell subsystem is controlled by three solenoid valves, a pressure actuated check valve, and a pressure sensor that signals the control microprocessor to shut down the power plant if the line pressure exceeds 14 kPa (2 psi).

3.2.3 Startup Burner

The startup burner used for providing stack warmup heat by combusting reformer product is shown in Figure 3.8. Combustion air enters through an annular space between the combustion chamber and the cover cylinder and travels the length of the combustion chamber before entering it at the upstream end through the air sealing damper. This flow arrangement preheats the combustion air and reduces the combustion chamber skin temperature. The air entering the combustion chamber mixes with the fuel and passes over the ignitor (platinum metal monolith catalyst). A deflector ring located immediately downstream of the ignitor aids mixing of the air and fuel during combustion.

3.3 ELECTRICAL SUBSYSTEM

This subsystem includes all ancillary components required for powering and controlling the electrically driven elements of the power plant. A block diagram of the electrical system is shown in Figure 3.9.

3.3.1 Starting Battery and Battery Charger

Starting power for the power unit is supplied by an onboard 24-volt battery. The battery consists of 20 high rate, 13Ah Ni-Cd cells.

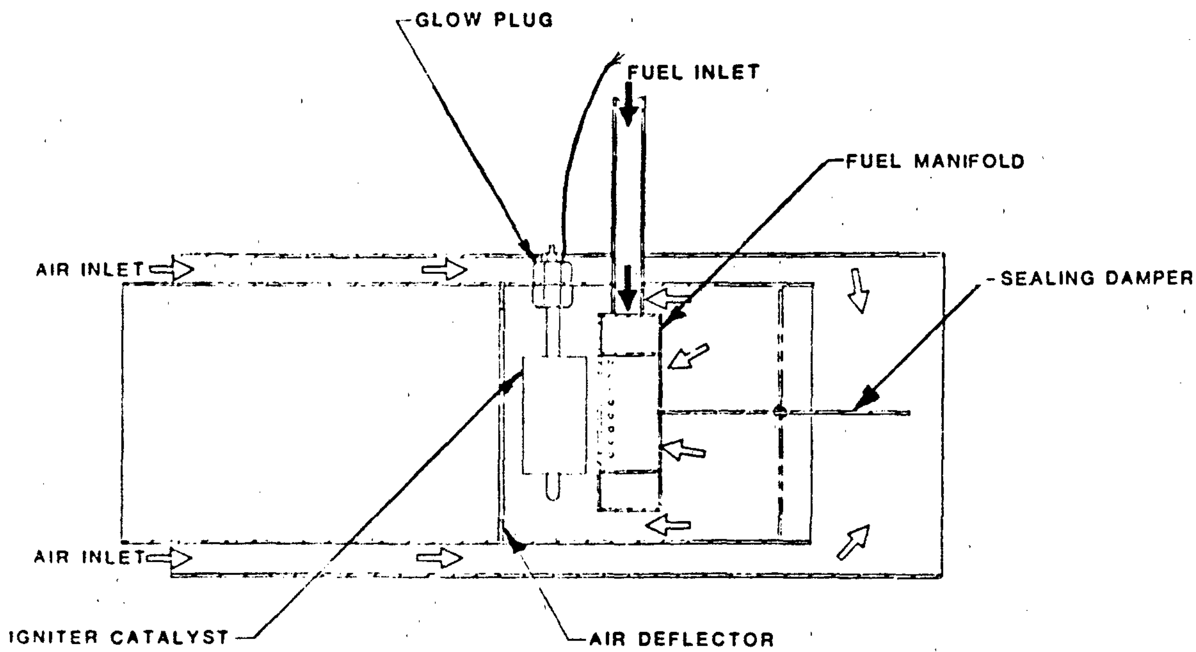


FIGURE 3.8
STARTUP BURNER

SD0001R1

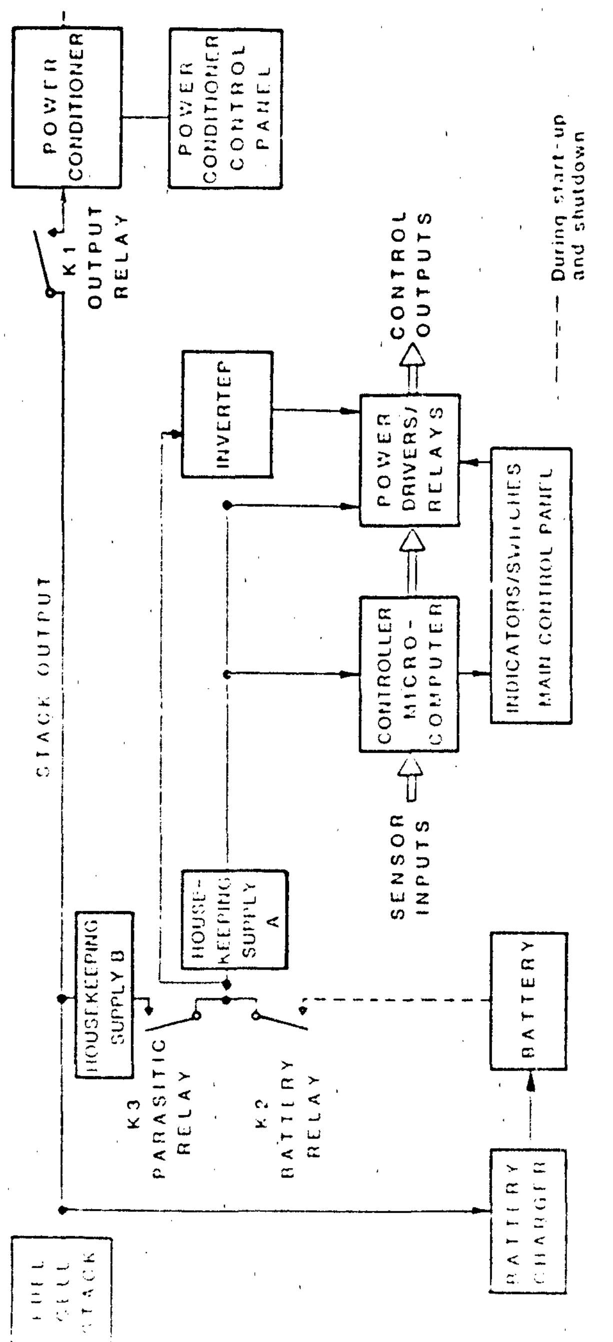


FIGURE 3.9
ELECTRICAL SYSTEM - BLOCK DIAGRAM

SD0113R1

The battery is recharged by a 3A onboard charger which is powered directly by the stack. A snap-action thermostat which activates at about 65 + 3°C provides overheating protection for the battery. When the battery reaches full charge voltage, the charger switches off automatically and the charge indicator light on the control panel goes off.

3.3.2 Housekeeping Power-Supply

The housekeeping power supply provides the regulated DC output necessary to operate the power plant. This output is used to power the following loads:

1. ±24 VDC: powers fuel cell stack blower inverter, solenoids, motors, relays, and pumps.

2. 5 VDC: powers the fuel injector.

3. 5 VDC, ±15 VDC: powers the microprocessor control system.

The housekeeping power supply consists of two independent power supplies (Unit A and Unit B) housed in a common enclosure. Unit B supply produces 24 VDC for the bus. Unit A supply provides isolated +5 VDC and ±15 VDC for the microprocessor. It also provides +5 VDC to power the injector and 24VDC for the power driver. This DC to DC converter operates either from the regulated 24 VDC bus or from the internal battery.

A separate 400 Hz, 115 VAC inverter powers the stack air blower. This inverter is also powered by the 24V bus.

3.3.3 Connectors

An auxilliary startup power connector is used for connecting an external battery or other 24-volt power source in case of insufficient output from the internal battery. The connector accepts the plug used on a standard NATO tank cable.

A ground connector provides a means for grounding the power plant.

3.3.4 Electrical Control Subsystem

The control subsystem consists of a controller microcomputer, a power driver assembly, a relay assembly, and a main control panel containing operator's controls and indicators. All of the control subsystem components are powered from the housekeeping power supply.

Inputs to the microcomputer include temperature sensors located in the fuel reformer and fuel cell stack assemblies, and stack voltage and current measurements. The microcomputer provides output to the main control panel indicators and the power driver/relay circuits. A listing of microprocessor input/output channels is given in Appendix B.

A. Microcomputer

The controller microcomputer assembly contains four printed circuit boards (an analog module, a CPU module and two isolator modules for input and output signals). This microcomputer was designed, assembled and programmed by Consolidated Controls Corporation, Danbury, CT. The microcomputer uses an Intel 8051 series CPU module having 8K bytes of memory. The program is written in machine language and stored in the ROM.

The main control panel shown in Figure 3.10 contains switches, meters, and indicators and provides the operator with the means for starting, stopping, and monitoring the operation of the power plant. A description of the power plant control panel is given in Table 3.2.

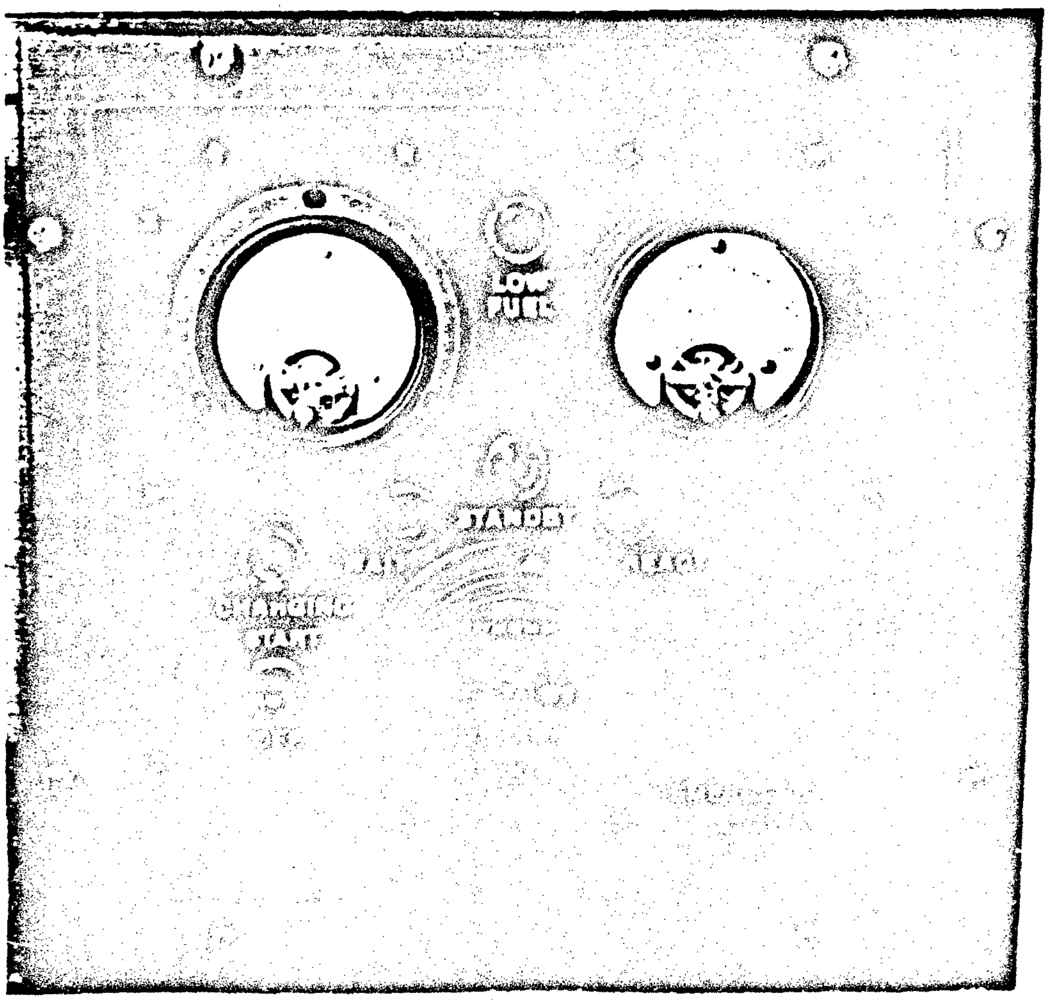


FIGURE 3.10
A PHOTOGRAPH OF THE POWER PLANT CONTROL PANEL

SP0036

TABLE 3.2

MAIN CONTROL PANEL - CONTROLS AND INDICATORS

CONTROL/INDICATOR	DESCRIPTION
START/OFF	Three position switch with spring return to center position. START initiates startup. OFF initiates shutdown.
EMERGENCY STOP	Guarded switch, normally OFF, must lift guard to move to STOP position. Used for emergency shutdown only.
LOW FUEL	Panel light, push-to-test, twist-to-dim. Lit when fuel in the internal reservoir is below 8 minutes of full load 3kW operation.
CHARGING	Panel light, push-to-test, twist-to-dim. Lit when battery is charging.
WAIT	Panel light, push-to-test, twist-to-dim. Lit during shutdown, must be off to restart.
STANDBY	Panel light, push-to-test, twist-to-dim. Lit during startup before unit is ready to supply power.
READY	Panel light, push-to-test, twist-to-dim. Lit when unit is ready to supply power.
DC VOLTS	0-75V DC Voltmeter. Indicates fuel cell voltage.
DC AMPERES	0-150A DC Ammeter. Indicates fuel cell current.
TOTAL HOURS	0-9999 digital meter. Displays total operating time of unit.

B. Power Driver Assembly

The power driver circuits which handle the control of power to the ancillary components are controlled by the microprocessor and by the opto-isolated digital interface. The power drivers are physically isolated from the microprocessor to enhance noise and heat rejection. A description of the power driver functions is given in Table 3.3.

3.4 POWER CONDITIONER

The power plant can be used with either an AC or DC output power conditioner. A corresponding control panel provides an operator switch and indicators for turning on or off power and monitoring power to the external load. The control panel is changed on the power plant together with the power conditioner.

The DC power conditioner for the 3kW power unit (a photograph is shown in Figure 3.11) was developed by Bikor Corporation (Torrance, CA). The controls and indicators on the DC power conditioner control panel are listed in Table 3.4.

The AC power conditioner contains a covered switch box containing two output selector switches. A Frequency Select Switch allows selecting either 60 Hz or 400 Hz output. An Output Select Switch allows selecting either 120V single phase parallel, 120/208V 3 phase, or 120/240V center tapped output configurations.

3.5 FRAME AND STRUCTURAL SUBSYSTEM

The frame and structural subsystem consists of a frame, a base plate, a skid base, and shock mounts. The design details for the 3kW power plant frame structure are shown in Figure 3.12. The frame for the 3kW power unit is designed to meet rough handling requirements. It is made from 1.9 cm (3/4 inch) AISI 4140 chrome molybdenum square tubing with a .12 cm (0.049 inch) wall thickness. Horizontal struts are used for subsystem and panel mounting.

TABLE 3.3

DESCRIPTION OF POWER DRIVERS

ITEM	DESCRIPTION
RELAYS AND SOLENOIDS	Switched on and off through tr. stor switches.
BURNER FAN	The burner fan is servo controlled by a 0-20 VAC variable voltage and a 0-262 Hz variable frequency power supply.
FUEL PUMP	The fuel pump is turned on and off by transistors that are controlled through the microprocessor. Float switches supply the microprocessor with signals to turn the fuel pump on and off, to light the low fuel warning light, and to shutdown the power plant under no fuel conditions.
INJECTOR	The injector is driven by a pulse train generated from a transistor switch. Fuel is adjusted by changing the frequency of the pulse train.
SEALING DAMPERS	The dampers are controlled by an on/off transistor switch which changes polarity of the applied power to the motors.
CONTROL DAMPERS	The control damper is operated by a power amplifier servo. The microprocessor supplies the reference position of the damper.

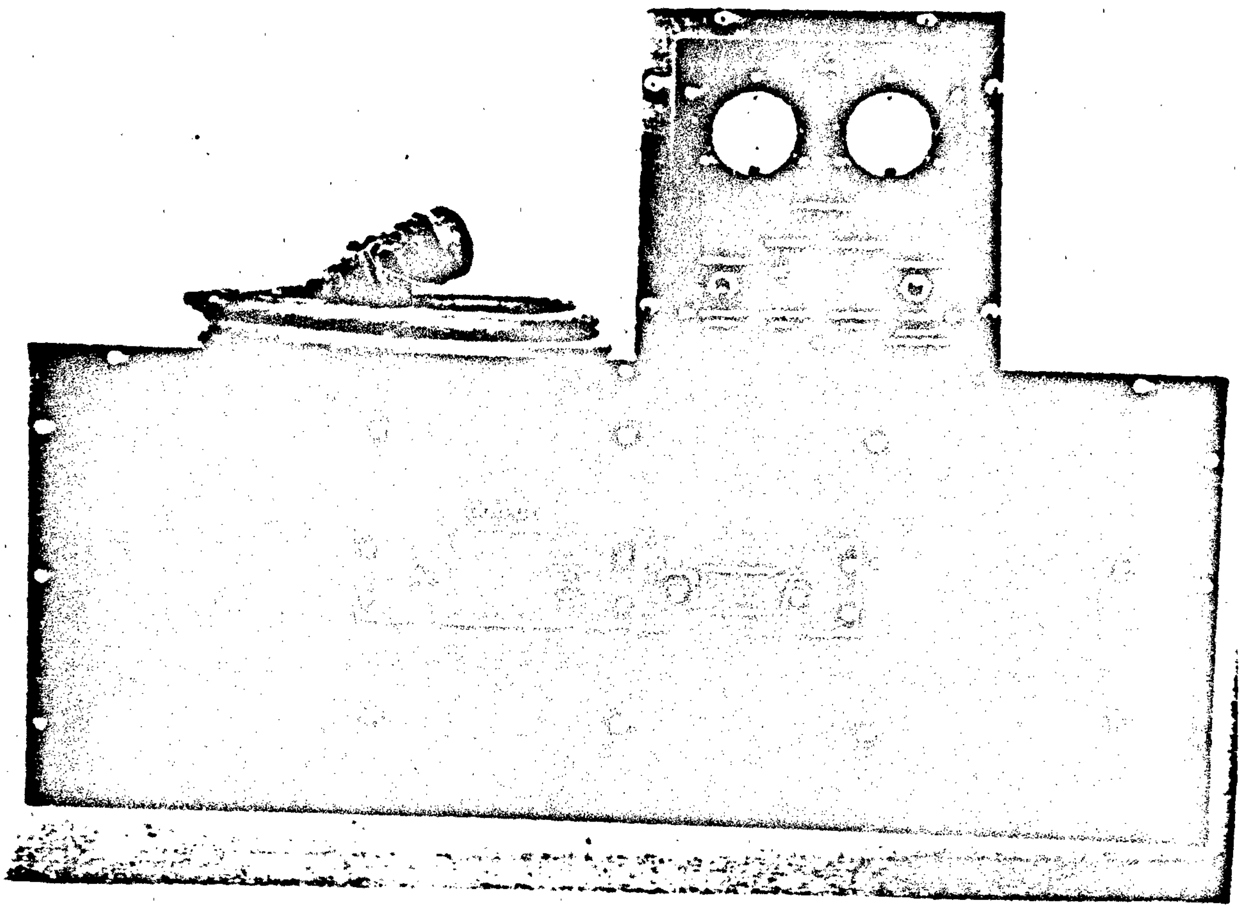


FIGURE 3.11 A PHOTOGRAPH OF THE 3kW DC POWER CONDITIONER AND POWER CONDITIONER CONTROL PANEL

SP00

TABLE 3.4

DC POWER CONDITIONER CONTROL PANEL - CONTROLS AND INDICATORS

CONTROL/INDICATORS	DESCRIPTION
DC VOLTMETER	Indicates voltage being supplied to the output terminals.
DC AMMETER	Indicates current being supplied to the output terminals.
OVERLOAD-OUTPUT	Panel light comes on to warn that over-current is being drawn from the Power Conditioner output terminals.
OVERLOAD-THERMAL	Panel light comes on to warn that internal temperature of the Power Conditioner exceeds the rated maximum.
POWER MONITOR LAMP	Panel light located directly below the DC Ammeter. Remains on so long as the Power Monitor is receiving normal power from the fuel cell.
NORMAL/CHARGE MODE	Two position toggle switch. NORMAL position is for normal loads that require a constant voltage source. CHARGE is for charging batteries which require a constant current source.
VOLTAGE ADJUST	Rotary control used to adjust output voltage when the MODE switch is on NORMAL.
CURRENT ADJUST	Rotary control used to adjust output current.
OUTPUT CONNECTOR	Three position switch with spring return to center position. CLOSE connects power to the Power Conditioner output terminals. OFF disconnects power to the output terminals.

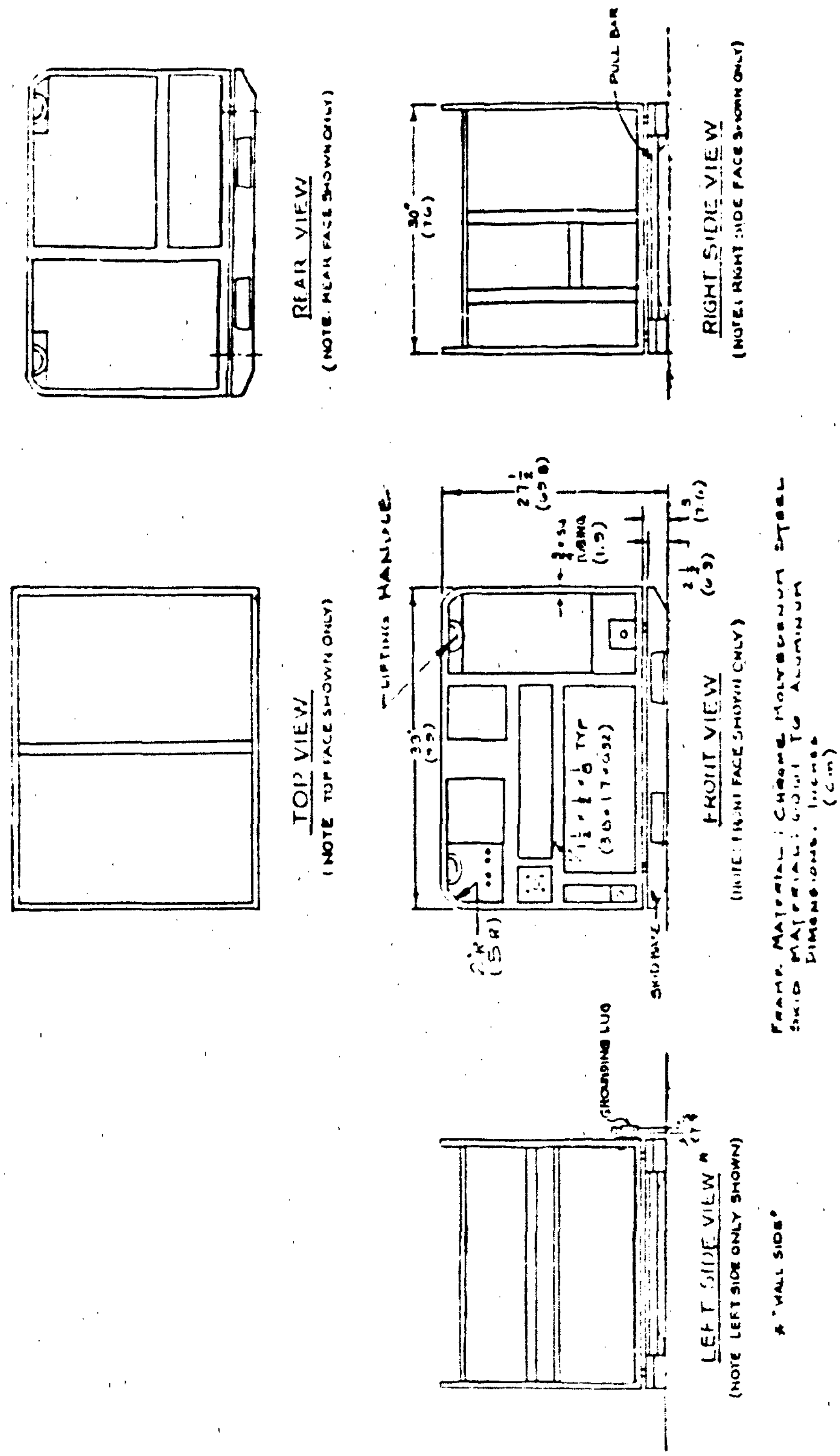

TOP VIEW
(NOTE: TOP FACE SHOWN ONLY)
REAR VIEW
(NOTE: REAR FACE SHOWN ONLY)
RIGHT SIDE VIEW
(NOTE: RIGHT SIDE FACE SHOWN ONLY)
PULL BAR
30"
(76)
LIFTING HANDLE
FRONT VIEW
(NOTE: FRONT FACE SHOWN ONLY)
LEFT SIDE VIEW *
(NOTE LEFT SIDE ONLY SHOWN)
* "WALL SIDE"
GROUNDING LUG
Frame Material: Chrome Molybdenum Steel
Skid Material: 6061 T6 Aluminum
Dimensions: Inches
(cm)

FIGURE 3.12

Four lifting attachments secured to the upper corners of the frame are designed to lift eight times the weight of the power plant. The top corners of the frame are rounded to a three-inch radius.

The base plate structure is a 0.31 cm (1/8 inch) thick aluminum deck with a 1.9 cm (3/4 inch) tubular frame. The base structure encloses the bottom of the power plant and prevents entry of debris into the unit. Drain holes are provided to prevent accumulation of liquid in the set. Elastomeric shock mounts, mounted in compression between the frame structure and the skid base, isolate all power plant subsystems to reduce shock and vibration.

THIS PAGE INTENTIONALLY LEFT BLANK

4.0 PERFORMANCE OF THE 3kW POWER PLANTS

The 3kW DC and AC prototype power plants, designated Models MEP 050A and MEP 051A, were evaluated for automatic startup, load following capability, fuel consumption, startup power and internal power consumption. The DC unit was run for about 100 hours at several output power levels to check for performance stability. The test schedule was as follows:

- 5 hours at idle
- 24 hours at 25% of full load
- 24 hours at 50% of full load
- 24 hours at 75% of full load
- 20 hours at full load

During this 100-hour test period, the longest continuous run was 42 hours. Several involuntary test interruptions occurred due to an intermittent electrical fault in the controller, which was later identified and corrected. A shutdown was related to stack air blower failure. This failure was unrelated to the endurance test and was traced to over temperature operation of the blower during startup burner developmental testing prior to the endurance testing.

Also, after completion of 3/4 of full load testing, the test run was temporarily discontinued following detection of sediment in a batch of fuel. The source of the sediment was traced to a vendor supplied CH_3OH drum. The SEM, EDAX, Emission Spectroscopy and Infrared Spectroscopy analyses performed showed the sediment to be a natural resin, possibly a modified maleic resin type. The reformer catalyst may have been affected by the contaminant. The contaminated catalyst was subsequently replaced with a fresh batch of catalyst.

The DC and AC units completed over 100 and 50 successful automatic starts, respectively, requiring less than 15 minutes for initial starts at room temperature and less than 3 minutes if restarted warm immediately after shutdown (Table 4.1). Premixed liquid fuel consumption for room temperature startup was approximately 1250 gms. About 90 Whr of electrical output from the onboard 24V Ni-Cd battery was required for a room temperature start.

Full warm startup required about 95 gms of premixed fuel and 17 Whr of electrical energy. Three minutes were required to completely shut down the power plant. Typical stack and reformer thermal profiles during startup are shown in Figures 4.1 and 4.2. Battery current and voltage profiles obtained during the startup period are given in Figure 4.3.

Voltage and power curves for the 3kW power plant with DC output are shown in Figure 4.4. About 4 kW is developed by the fuel cell stack for a net power plant output of 3 kW DC. The discontinuities in the power curves are due to the four internal stack heaters. These heaters are located in the stack air manifold and maintain stack current and temperature at low loads. As load current increases, the heaters are progressively disconnected.

The key operating parameters for the 3kW power plant with its DC and AC output are listed in Tables 4.2 and 4.3, respectively.

Methanol-water premix consumption for the DC unit is plotted in Figure 4.5. It varied from 2.4 liters/hour at idle to 4.0 liters/hour at 3 kW. At rated load neat methanol consumption was 0.68 kg/kWhr which corresponds to an overall power plant thermal efficiency of 26% (LHV). For 3kW AC operation the overall thermal efficiency was 23% (LHV). Loss of fuel cell voltage with aging will result in increase in fuel cell stack current and, therefore, fuel consumption to deliver the rated output power.

TABLE 4.1

ENERGY CONSUMPTION DURING START/STOP OPERATIONS

OPERATION	TIME TO START/STOP min.	ENERGY CONSUMPTION	
		PREMIXED FUEL gm	ELECTRICITY (From 24V Battery) Amp-hr
STARTUP			
Stack and Reformer at 24-27^{o}C	14$\pm$0.5	1250$\pm$20	4$\pm$0.2
Stack and Reformer fully warm	2.75$\pm$0.25	95$\pm$10	0.7$\pm$0.06
STOP	3.0	0.0	0.50

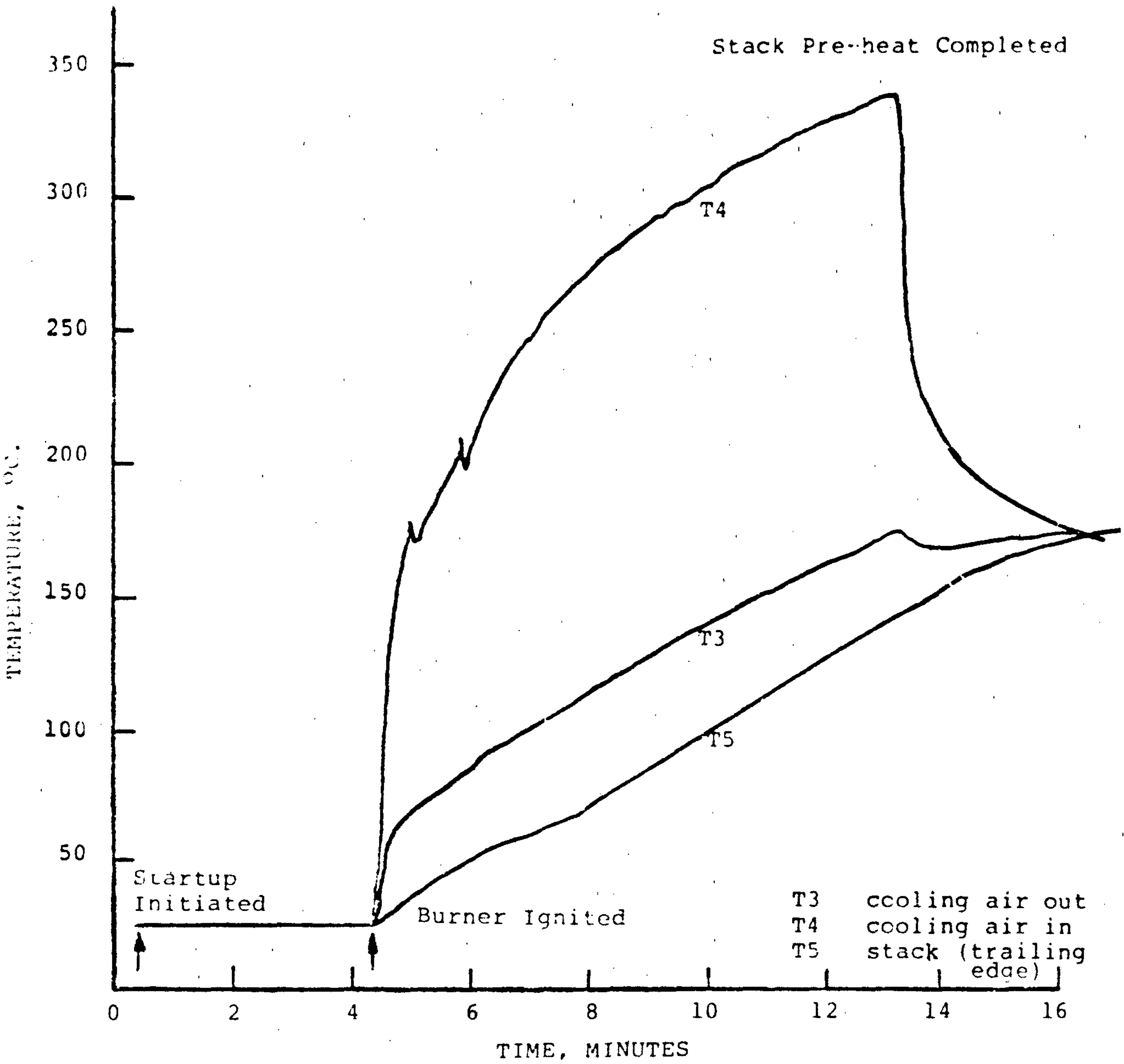


FIGURE 4.1
FUEL CELL THERMAL PROFILE DURING STARTUP
(Premixed fuel flow: 49 gm/min through nozzle; 53 gm/min through RI)

SD0134R1a

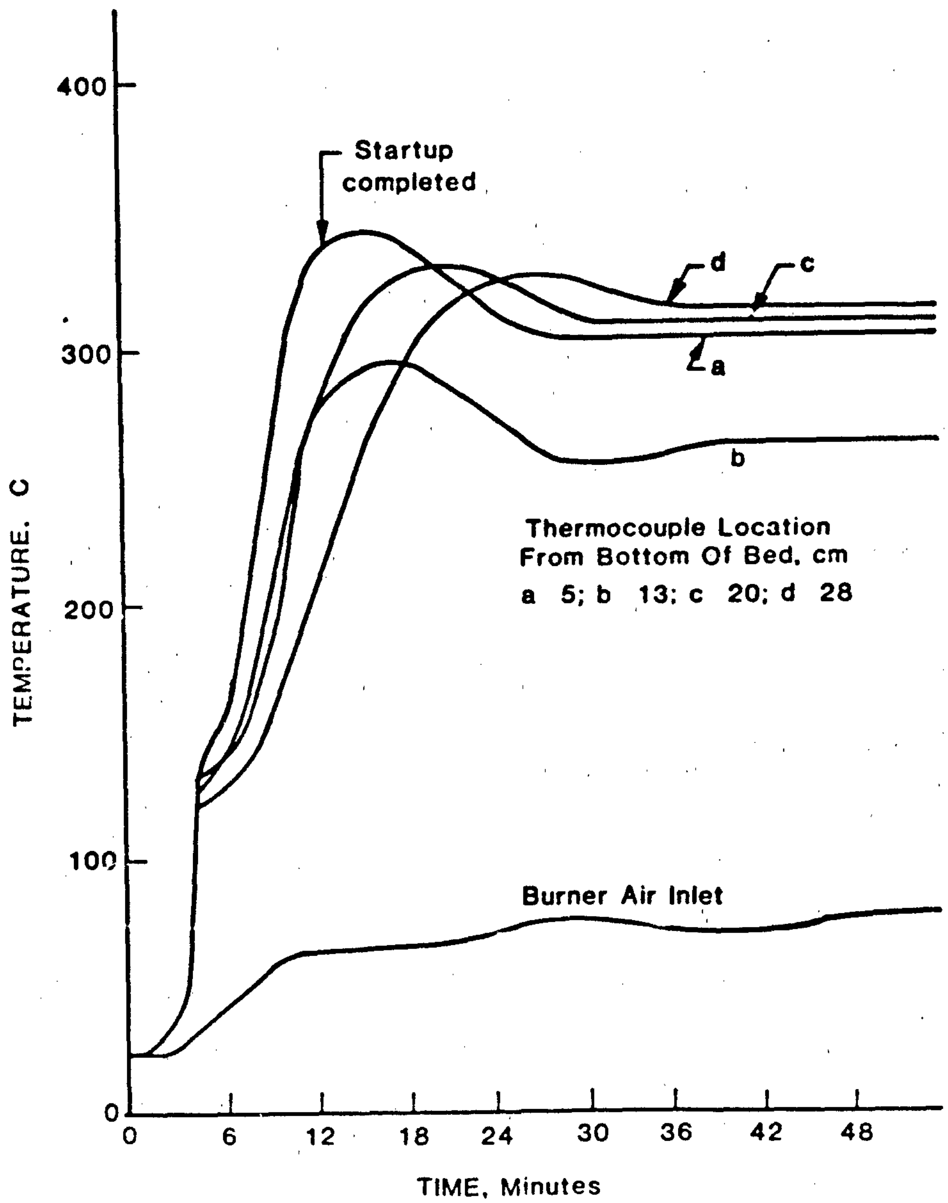


FIGURE 4.2
REFORMER THERMAL PROFILE DURING STARTUP

SD0153R2

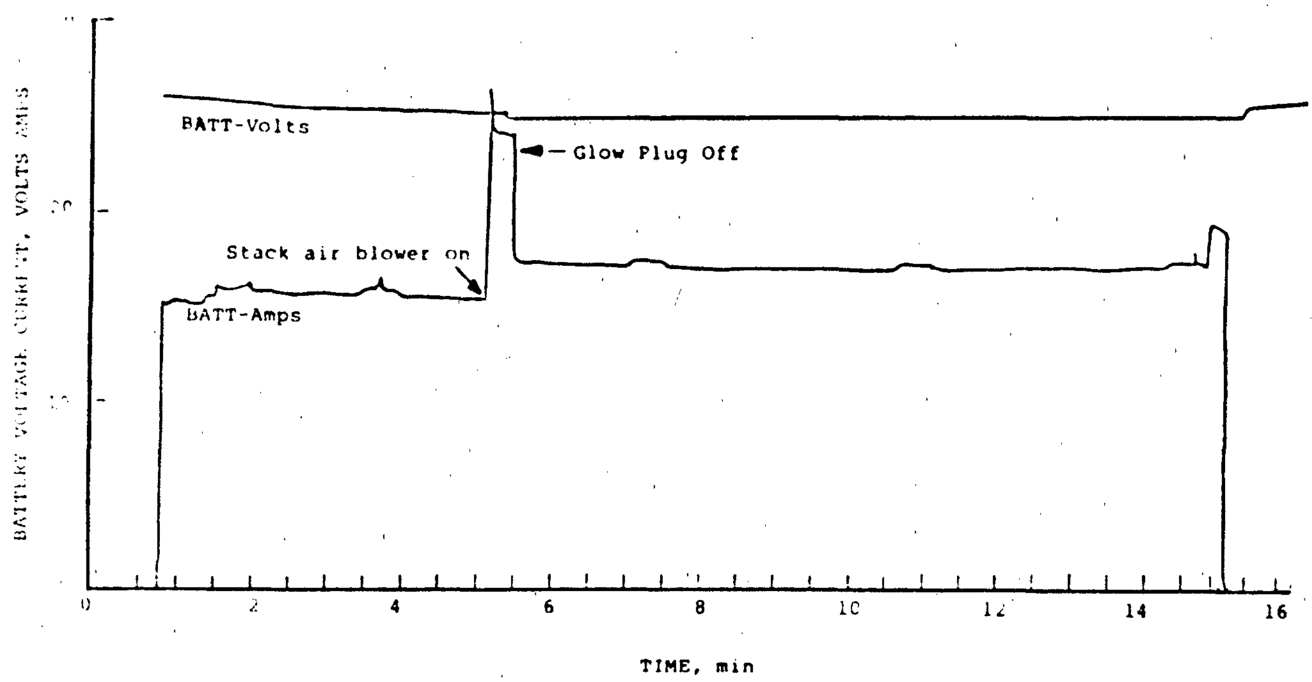


FIGURE 4.3
CURRENT-VOLTAGE PROFILE OF THE BATTERY DURING STARTUP

SD0133R2

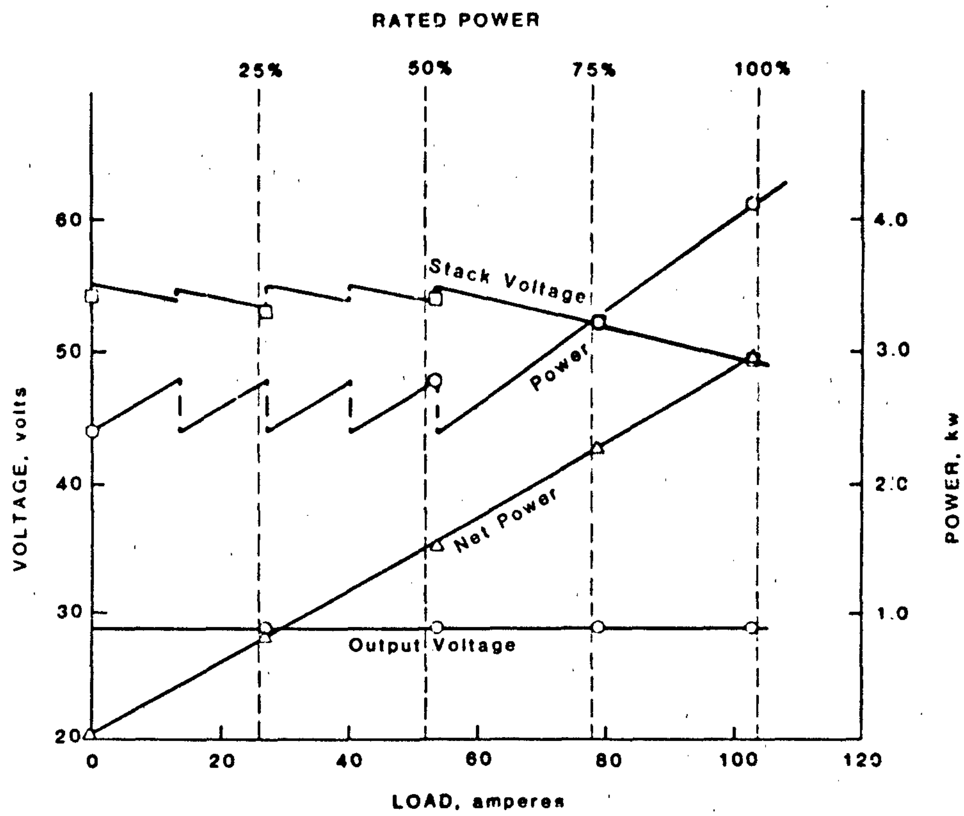


FIGURE 4.4

VOLTAGE AND POWER CURVES FOR THE 3kW
FUEL CELL POWER PLANT (DC OUTPUT)

SD0142R1

TABLE 4.2
OPERATING PARAMETERS WITH DC OUTPUT

(a) DC Output

POWER RATING	IDLE	1/4	1/2	3/4	FULL
External Load					
Volts	-	28.9	28.8	28.8	28.5
Amperes	-	26.9	53.4	78.9	103.9
Watts	-	777	1538	2272	2961
Stack					
Volts	54.2	53.1	54.1	52.8	48.5
Amperes	48.1	51.2	51.5	61.2	80.7
Watts	2607	2719	2786	3231	3914
Air Out, °C	182	178	176	176	178
Air In, °C	154	148	147	144	132
Reformer Bed, °C	345	343	330	324	256
Fuel Consumption, gm/min	39.8	42.8	41.8	48.0	58.6
Efficiency					
Overall, %	-	9	19	25	26

TABLE 4.3

OPERATING PARAMETERS WITH AC OUTPUT

(b) AC Output (3 Phase, 60Hz)

POWER RATING	IDLE*	1/2*	3/4*	FULL
External Load				
Average Volts	-	119	119	119
Average Amperes	-	3.8	5.6	7.4
Watts	-	1357	2010	2641
Stack				
Volts	54.7	53.2	52.5	50.7
Amperes	47.7	48.7	64.0	81.0
Watts	2610	2590	3360	4106
Air Out, °C	179	160	184	187
Air In, °C	174	148	155	142
Reformer Bed, °C	322	337	316	271
Fuel Consumption, gm/min	36.3	39.7	49.7	59.0
Efficiency				
Overall, %	-	17.8	21.0	23.3

* Battery Charger was on

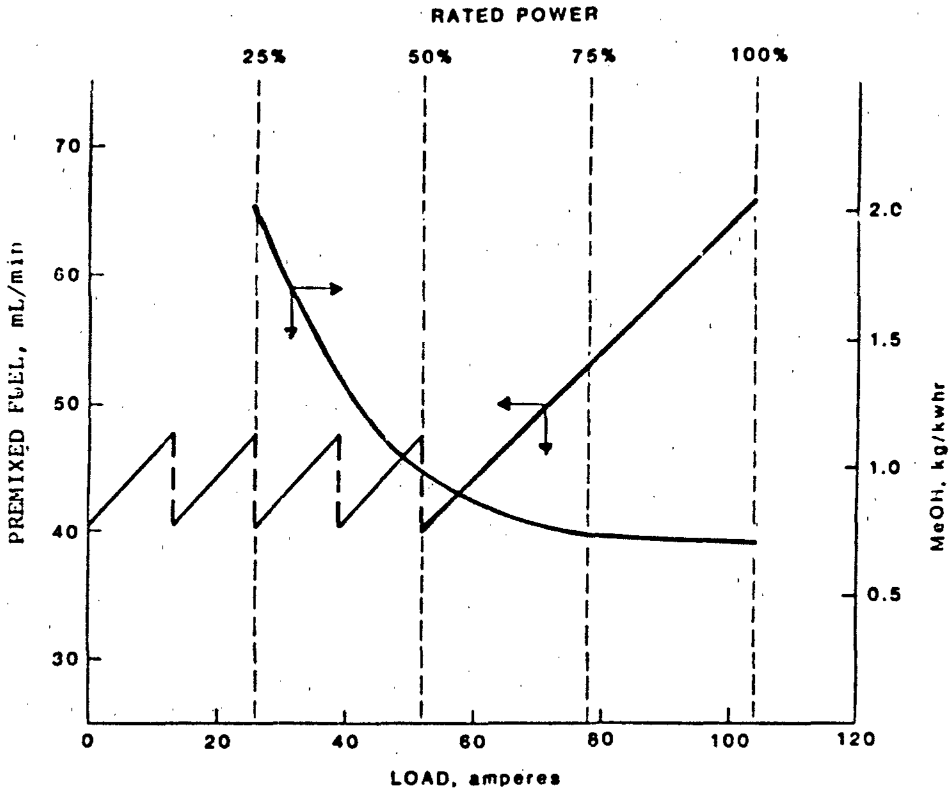


FIGURE 4.5

FUEL CONSUMPTION OF THE 3kW POWER PLANT
(DC OUTPUT)

SD01

Response to a step change in external load was tested. The power plant assumed rated 3kW load instantly from 1/4 load, 1/2 load and 3/4 load (Figure 4.6). From idle, the power plant was able to assume full load in about 60% of the attempts. The lack of consistant ability to instantaneously assume full load from hot idle standby is associated with the low rate of fuel processing at idle. Increasing the stack current in the idle mode will provide the higher standby fuel processing rate required for consistant upload capability.

A summary of internal housekeeping power supply and power conditioning efficiencies are reported in Table 4.4. The housekeeping power supply operated at an efficiency of about 82-86% and the DC regulator and the AC inverter efficiencies at full load were 89% and 75%, respectively. Parasitic power of 77-489 watts was drawn from the housekeeping power supply by the ancillary components.

The 3kW prototype power plants delivered met the goals for fuel consumption, room temperature startup time and start/stop power consumption. The unit required about 14 minutes for startup from room temperature. Approximately 18 and 20 minutes will be required to start the power unit from -31°C (-25°F) and -54°C (-65°F) ambient temperatures, respectively.

The power plant weight of 80 kg/kW (for DC output) and volume of 0.17 m^3/kW exceeded the goal for unit weight (45 kg/kW) and volume (0.11 m^3/kW). The power unit was capable of operating automatically with a variable output load. However, the unit was not able to reliably supply full load instantaneously from idle operation. Testing of noise level has not been performed. However, a fuel cell power plant of similar design delivered under a previous contract [2] satisfied the low noise requirement.

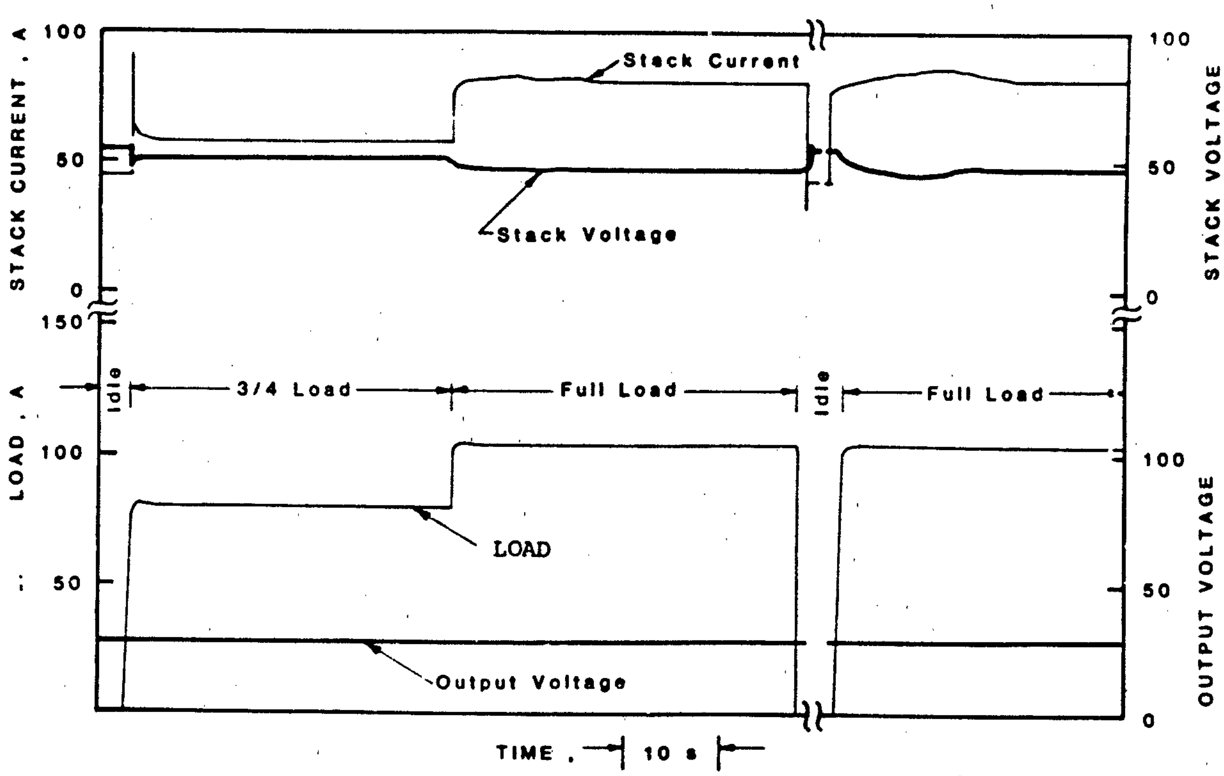


FIGURE 4.6

POWER PLANT RESPONSE TO LOAD CHANGE

SD0170

TABLE 4.4

HOUSEKEEPING SUPPLY AND POWER CONDITIONING EFFICIENCIES

a) 28 VDC OUTPUT

GROSS FUEL CELL POWER, kW	EXTERNAL LOAD kW	EFFICIENCY, %		
		HOUSE KEEPING POWER SUPPLIES	DC REGULATOR	OVERALL THERMAL
2.6	-	83	-	-
2.7	.8	82	86	9
2.8	1.5	85	88	19
3.2	2.3	85	88	25
3.9	3.0	84	89	26

b) 120V, 3-PHASE, $60H_z$ OUTPUT

GROSS FUEL CELL POWER, kW	EXTERNAL LOAD kW	EFFICIENCY, %		
		HOUSE KEEPING POWER SUPPLIES	AC INVERTER	OVERALL THERMAL
2.6	-	84	-	-
2.6	0.7	84	72	10
2.6	1.4	86	73	18
3.4	2.1	85	75	22
4.1	2.7	86	75	23

THIS PAGE INTENTIONALLY LEFT BLANK

5.0 BRASSBOARD POWER PLANT

Prior to construction of the 3kW prototype power plants, a 3kW brassboard power plant was constructed and tested. A number of design modifications and improvements evolved from the experience with the brassboard power plant and were incorporated in the prototype power plant design.

5.1 DESIGN

The brassboard power plant design was the basis for designing the prototype power plants discussed in Sections 2 and 3, except for the use of a direct air-cooled (DIGAS) fuel cell stack (described in Section 6) and modified power plant startup system.

A functional flow diagram of the brassboard power plant is given in Figure 5.1. Reformer flue gas was utilized for heating the fuel cell stack during the startup phase. Two injectors, one for reformer fuel and one for burner fuel, were used. The brassboard unit used a microprocessor based controller for automatic control, and a DC voltage regulator for output power conditioning. The controller was later simplified and used in the prototype power plants. A photograph of the 3kW brassboard power plant is shown in Figure 5.2.

5.2 BRASSBOARD POWER PLANT TESTING

A 100-hour test run was conducted to study steady state power plant operation, including fuel consumption at idle and various power levels, and ability to respond to stepwise changes in load.

The goal of this test was to operate the power plant continuously for 100 hours under conditions approximating field service. This effort was largely successful, although some interruptions were necessitated by equipment malfunctions.

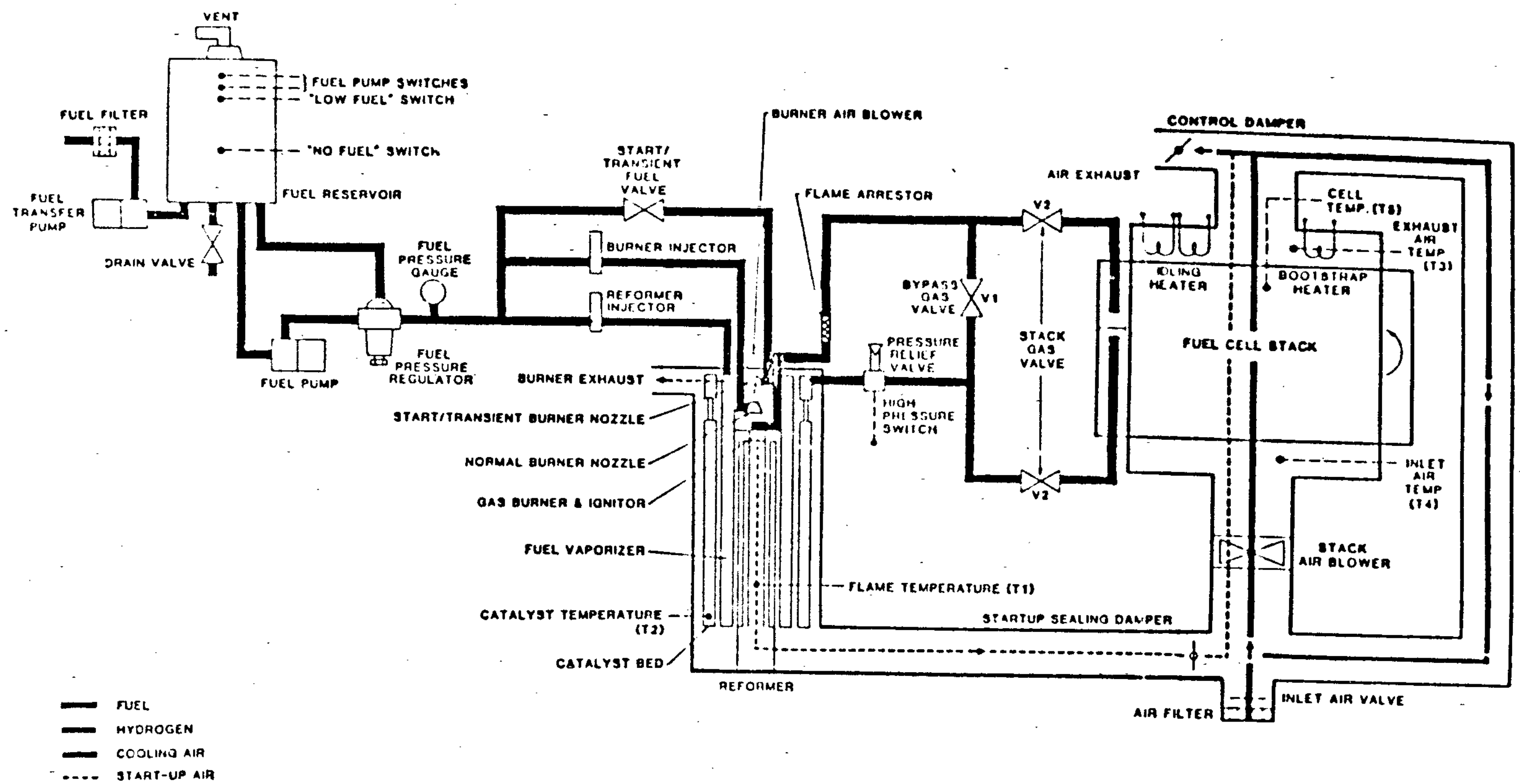


FIGURE 5.1
FUNCTIONAL FLOW DIAGRAM OF BRASSBOARD POWER PLANT

SD0205

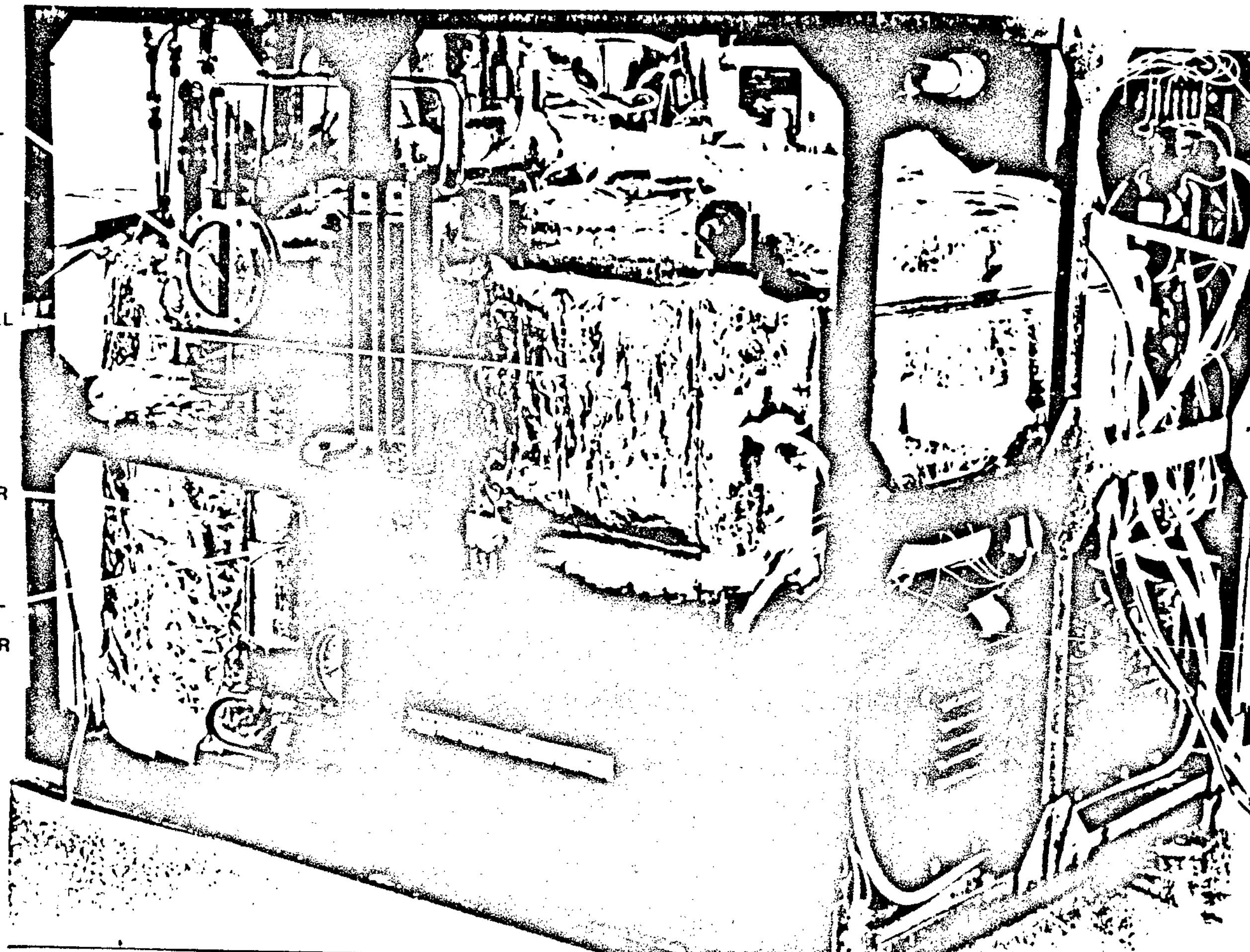


FIGURE 5.2 THE 3kW BRASSBOARD POWER PLANT

During the 100-hour test run, the power plant was run on the following schedule: 2 hours at idle, 27 hours at 1/4 load, 27 hours at 1/2 load, 26 hours at 3/4 load and 27 hours at full load.

The overall performance of the brassboard power plant is summarized in Table 5.1. Variation in output current and stack and output voltage with load is shown in Figure 5.3. Two internal stack heaters connected through relays across stack terminals were used to maintain stack temperature at low loads and caused the stepwise shift in stack current.

The fuel consumption data of the 3kW brassboard power plant are given in Figure 5.4. Methanol consumption varied between 1.0 kg/hr at idle to 2.45 kg/hr at full load. The fuel consumption of 0.81 kg/kWhr at full load corresponds to an overall power plant efficiency of 22% (LHV).

The response of the brassboard power plant to instantaneous external load change was also studied. The test results, shown in Figure 5.5, indicated ability to assume up to 3/4 load from idle; a 20-second delay at 3/4 load was adequate to reach full load.

Brassboard power plant startup was performed manually while simulating the microprocessor program logic. The test results raised several issues concerning startup.

- Reliability of a high temperature sealing damper (used in the startup duct).
- Exposure of reformer catalyst to high temperature.
- Acid dilution and introduction of incomplete combustion products in FC stack during warmup.

Based on the brassboard power plant test results, a modification in both startup hardware design and program logic was made for the prototype power plant.

TABLE 5.1

BRASSBOARD POWER PLANT PARAMETERS (DC OUTPUT)

EXTERNAL LOAD	IDLE	1/4	1/2	3/4	FULL
Volts	0	28.2	28.2	28.1	29.7
Amps	0	26.8	54.1	79.9	101.5
Watts	0	756	1526	2245	3015
STACK					
Volts	52.2	52.4	50.7	47.5	42.9
Amps	29.2	35.6	44.2	64.3	92.4
Air inlet temp., °C	--	165	158	146	132
Air outlet temp., °C	--	187	188	191	196
Plate temp., °C	--	194	196	198	209
RF CATALYST BED TEMP., °C					
5 cm from the leading edge	293	266	260	249	249
%CO IN REFORMER FUEL	--	1.9	2.3	2.0	1.2
FUEL CONSUMPTION					
RF g/min	27.6	31.6	38.6	47.6	68.5
B g/min	--	4.2	4.0	3.7	1.9
PARASITIC LOAD					
Watts	594	579	545	532	527

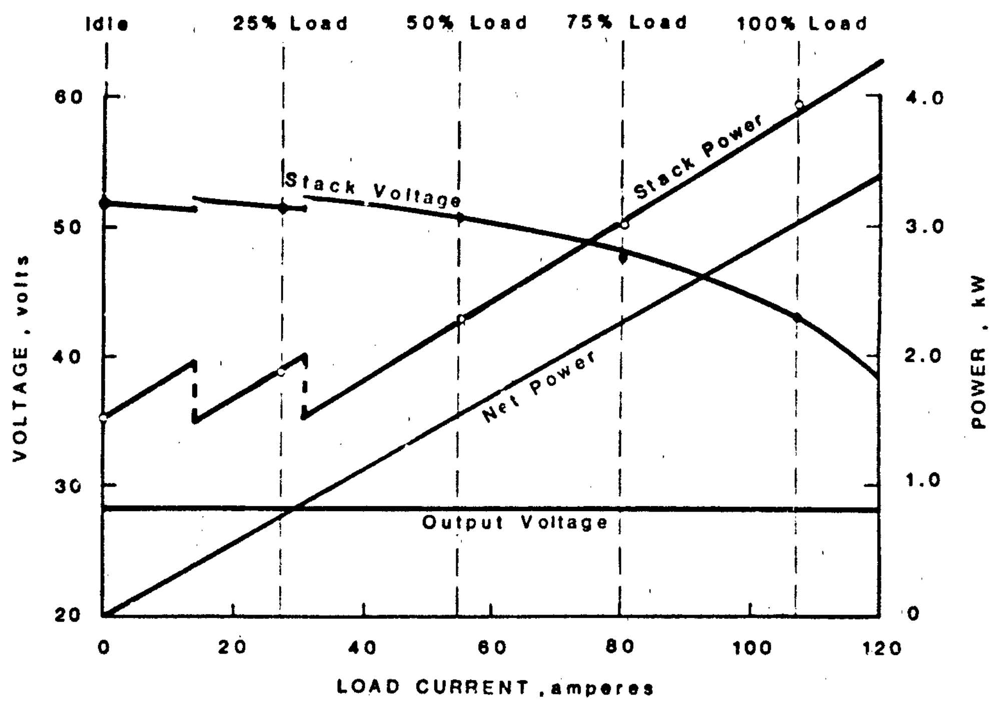


FIGURE 5.3
BRASSBOARD POWER PLANT PERFORMANCE

SD0204

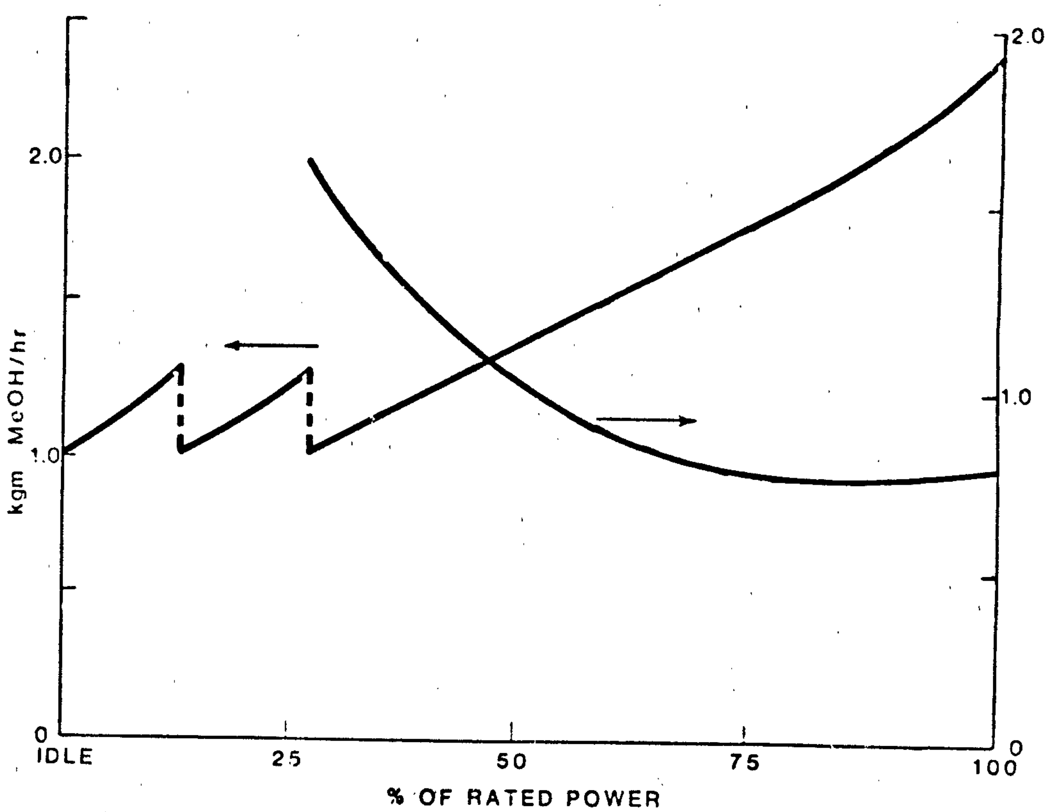


FIGURE 5.4

FUEL CONSUMPTION OF THE BRASSBOARD POWER PLANT

SD0030R

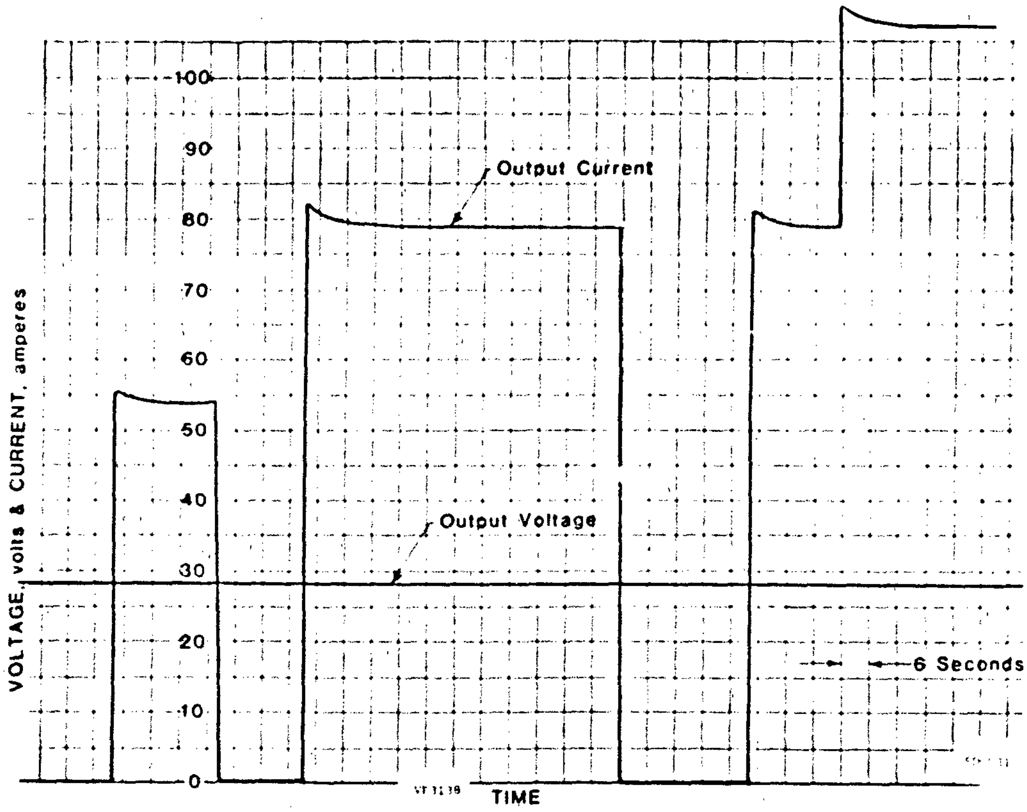


FIGURE 5.5

BRASSBOARD POWER PLANT RESPONSE TO TRANSIENT LOAD

6.0 COMPONENT DEVELOPMENT

Several key power plant components underwent design changes in the course of this project. A description of the intermediate designs and test data for these components are discussed in this section.

6.1 FUEL CELL STACK

An 80-cell stack using direct air-cooling (DIGAS), was initially designed for the 3kW fuel cell power plant. The key features of this design are summarized below:

- Bipolar and cooler plates measuring 17.5 cm x 42 cm (7" x 16.5").

- Cooling channels in every fifth cell with air flow split 1:4 between the process and cooling channels.

- Cooling side pressure drop of 4.3 cm (1.7") H_2O.

- Lightweight honeycomb end plates and hollow tie bars.

During the design phase, 10-cell and 80-cell, 12.5-cm x 38-cm (5" x 15") size stacks were constructed and tested to verify baseline performance, thermal management and fuel cell response to load transient. A 23-cell, 17.5-cm x 42-cm (7" x 16.5") size stack was also constructed and tested to confirm desired cathode to cooling air flow split, and to study thermal cycling and cold storage effects. Subsequent to successful testing of these stacks, the 80-cell, 17.5-cm x 38-cm (7" x 16.5") stacks were constructed.

Typical performance of the 17.5-cm x 38-cm (7" x 16.5') size, 80-cell DIGAS stack on reformed fuel is given in Figure 6.1. The DIGAS stack was used in the 3kW brassboard power plant.

While the DIGAS stack performed well, some electrolyte dilution occurred when the stack was warmed up from room temperature as evidenced by the formation of acid droplets on the cells. Since this condition would be aggravated by low ambient temperatures and could lead to electrolyte loss, an alternate stack design was adopted. This design, called the separate air cooling (SAC) design, provides separate air paths for cathode air and for cooling air as illustrated in Figure 6.2.

A 10-cell SAC stack and two 10-cell DIGAS stacks were built and tested for performance and stability comparison. The stacks underwent repeated startup from cold temperature. The startup heating was by burner flue gas directed through the common air channels of the DIGAS stack and through the cooling air passages of the SAC stack. An environmental chamber was used to cool the stacks before the low temperature starts.

Improved stability for the SAC stack with thermal cycling is indicated by the data in Figures 6.3 and 6.4. The drop in performance of the SAC stack at the 28th cycle was probably due to equipment failure which led to overheating of the warmup air and exposure of the stack inlet to a temperature in excess of 500°C.

A 40-cell SAC stack was constructed and delivered to the Army for evaluation. The stack before installation of manifolds can be seen in Figure 6.5

6.2 FUEL PROCESSOR COMPONENTS

6.2.1 Reformer Burner

Parallel development was pursued on an ultrasonic burner supplied by Sono-Tek Corp. (Poughkeepsie, NY), and on a conventional spray nozzle burner.

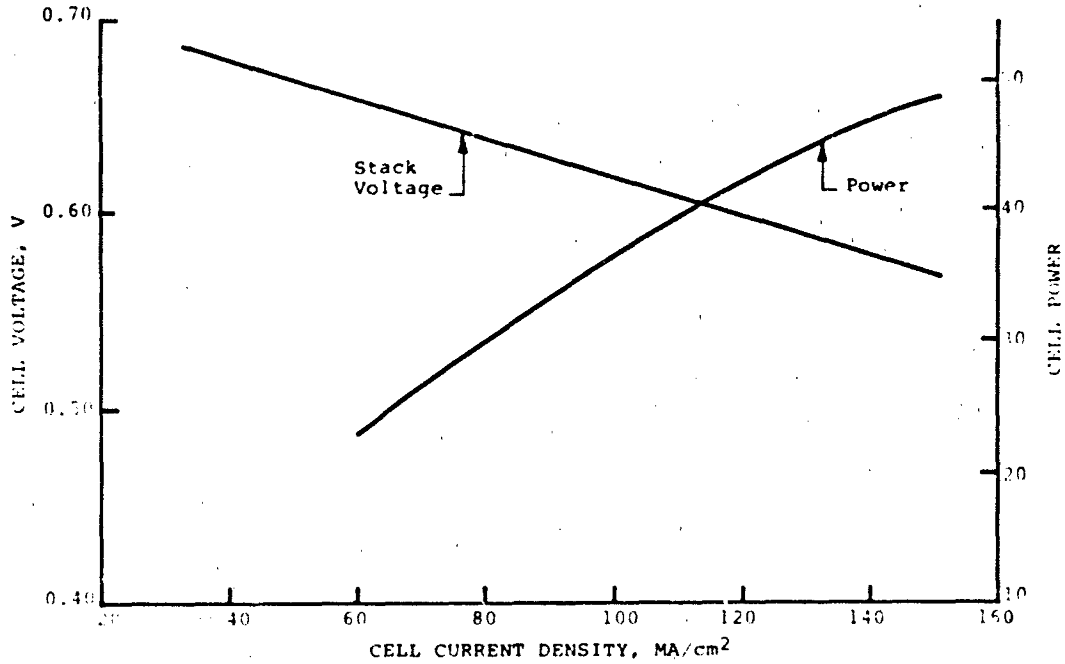


FIGURE 6.1

PERFORMANCE OF 80-CELL DICAS STACK WITH REFORMED METHANOL FUEL

SD0206R

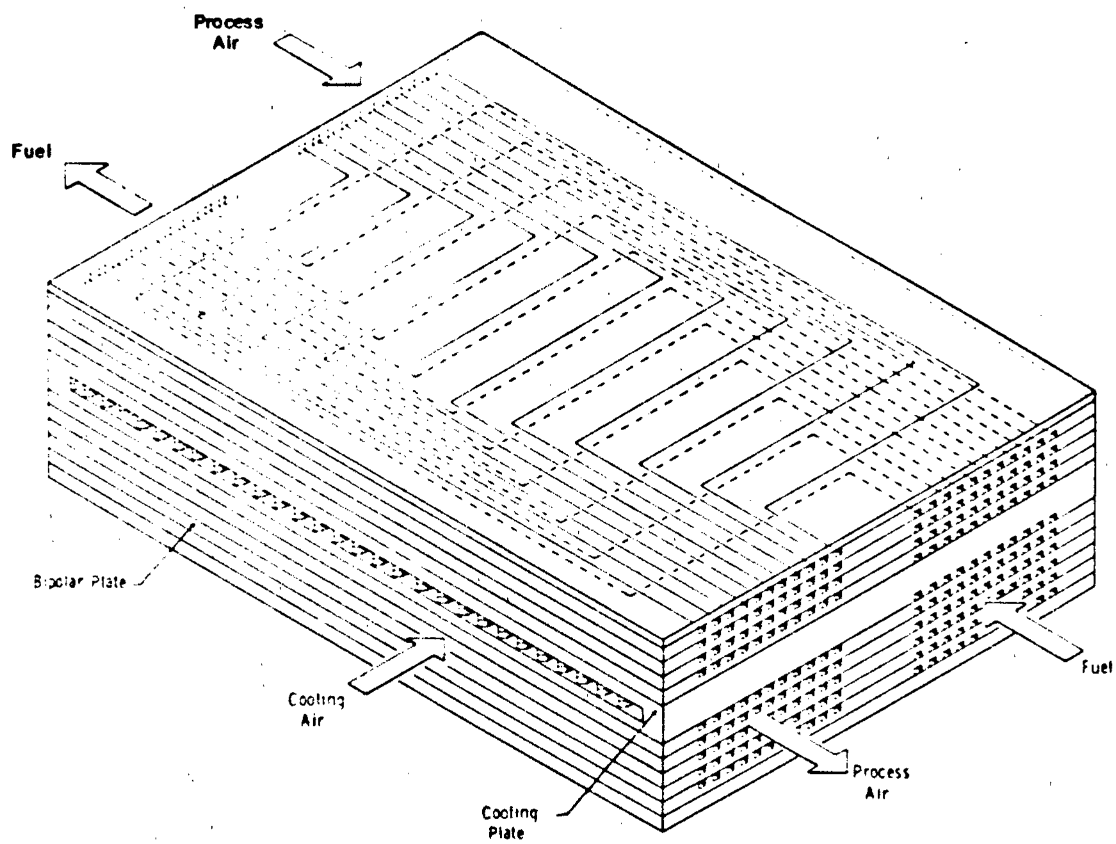


FIGURE 6.2
PERSPECTIVE VIEW OF THE SEPARATED AIR-COOLED STACK

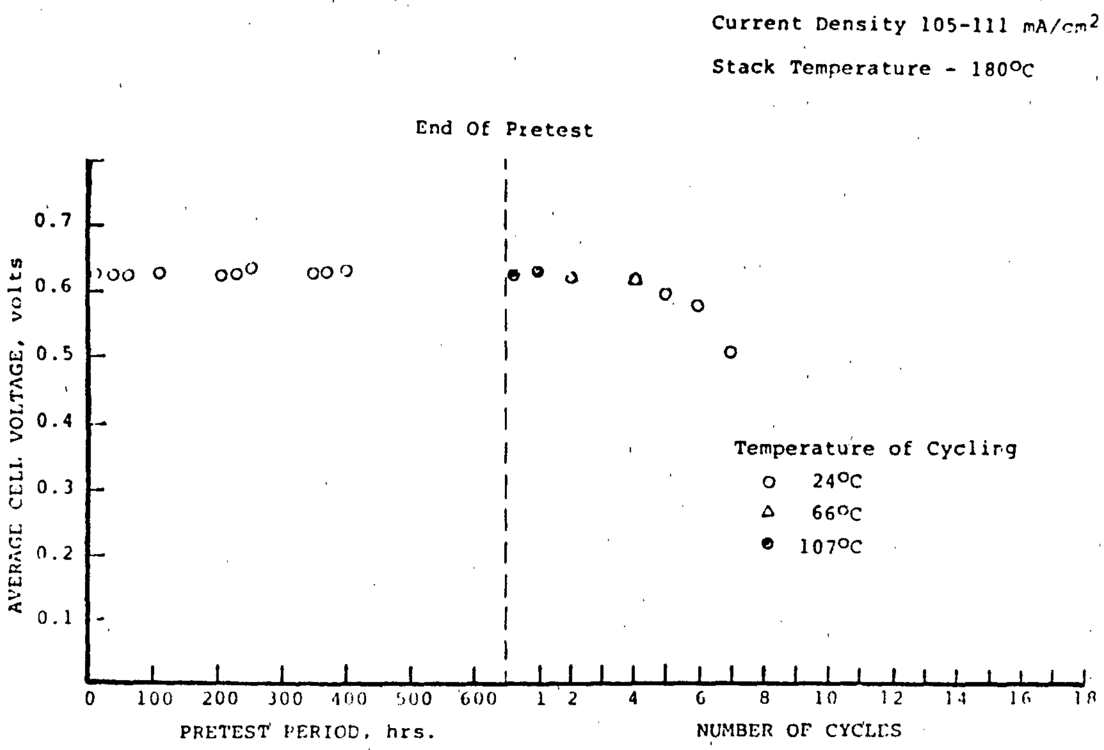


FIGURE 6.3

EFFECT OF TEMPERATURE CYCLING ON A 10-CELL DIGAS STACK

SD0207

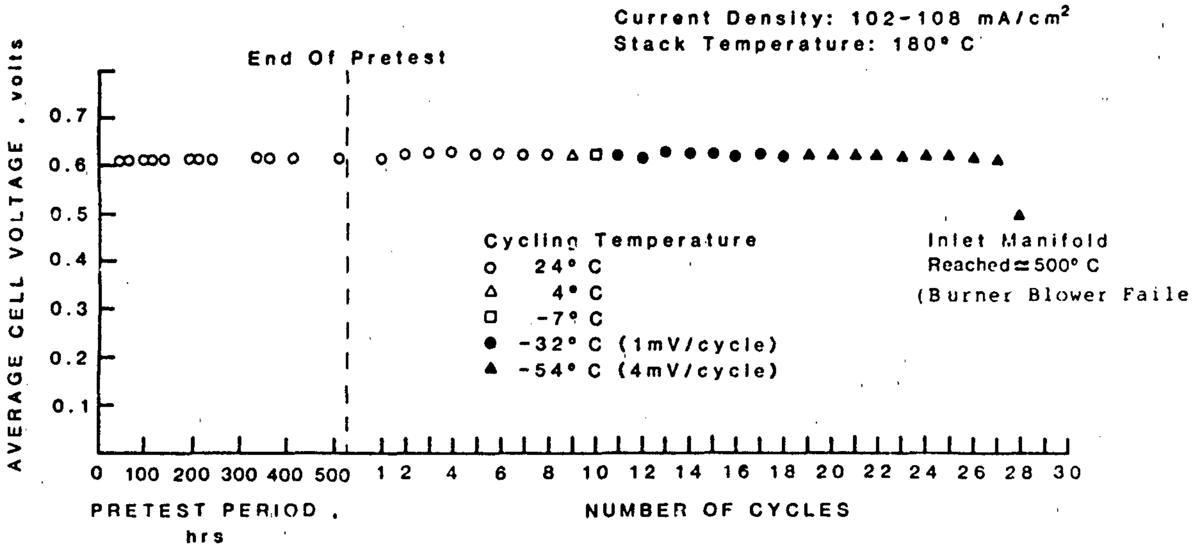


FIGURE 6.4

EFFECT OF CYCLING ON A 10-CELL SAC STACK

SD0208

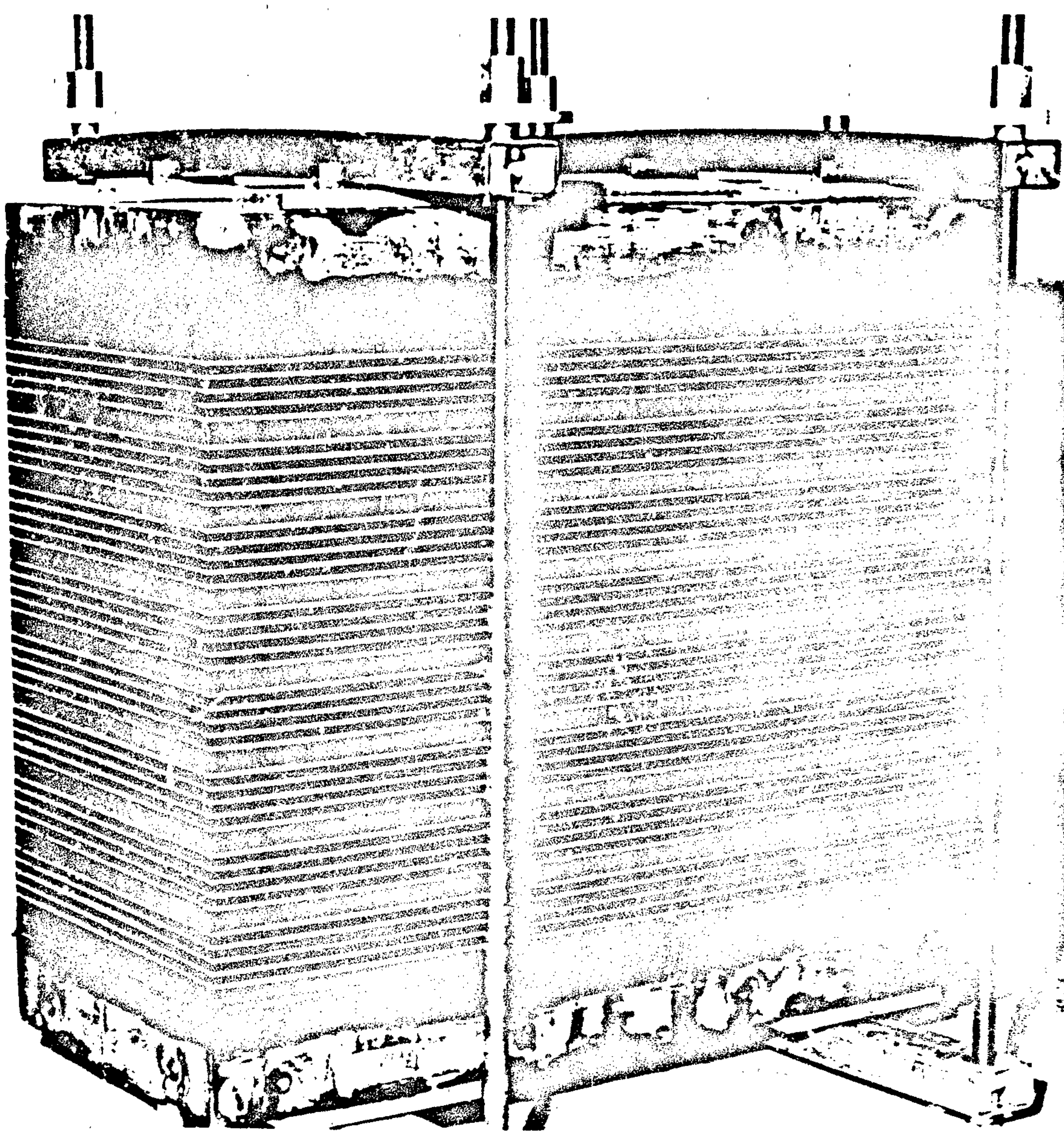


FIGURE 6.5 PHOTOGRAPH OF THE 40-CELL SEPARATED AIR-COOLED STACK

SP0039

The work on the ultrasonic burner was initiated because of earlier difficulties of igniting the low energy fuel methanol-water at temperatures below -32°C. The burner design consisted of a high frequency exciter circuit operated atomizer nozzle, a multi-speed air blower and an electronic spark ignitor. The ERC design consists of an axial fan, an oil burner spray nozzle and a glow plug for ignition.

Both burners were successfully tested for ignition at -25°F (-32°C) during this project, and had comparable combustion efficiency with premixed liquid fuel. Based on reliability and cost considerations, the ERC design was selected for the power plants. A photograph of the burner and burner components is shown in Figure 6.6.

6.2.2 Vaporizer/Superheater

The following vaporizer designs were studied:

- Double annular can (DAC)
- Packed bed DAC
- Annular can fitted with toroidal rings

Evaluation of these designs revealed that the annular can fitted with toroidal rings provided the best performance during rapid load changes. Reformers built with this vaporizer performed best in the brassboard power plant. The initial upflow arrangement in the vaporizer was changed to downflow, which reduced reformer output pressure fluctuation. This arrangement was used for the prototype power plants delivered to the Army.

6.2.3 Catalyst Bed

Catalyst performance and stability were verified by testing a subscale reformer tube containing United Catalyst T-2130 catalyst for 2000 start-stop cycles over a 3000 hour test period. The tube was operated at a relatively high space velocity of

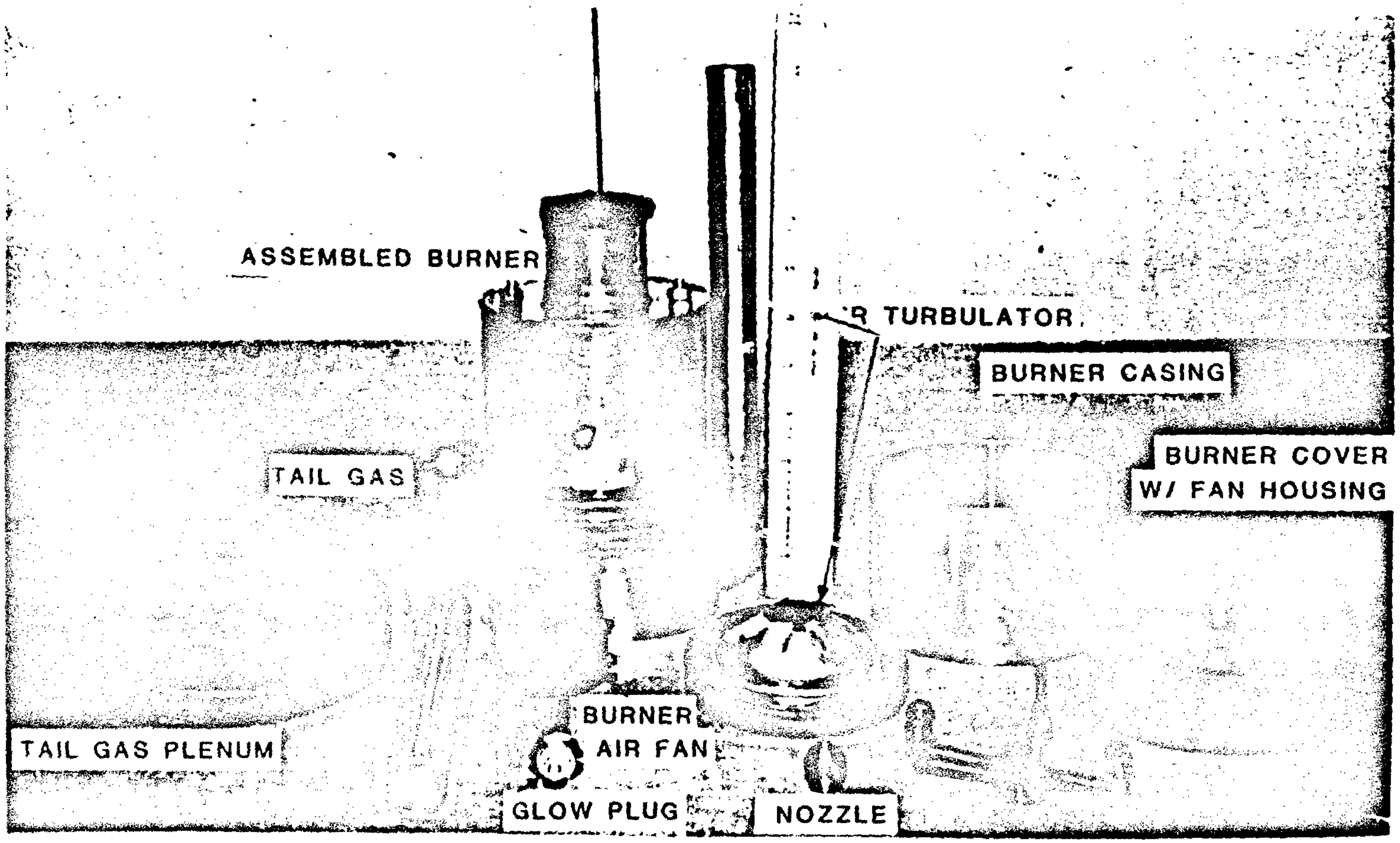


FIGURE 6.6

ERC 3/5kW REFORMER BURNER AND
BURNER COMPONENTS

SP0040

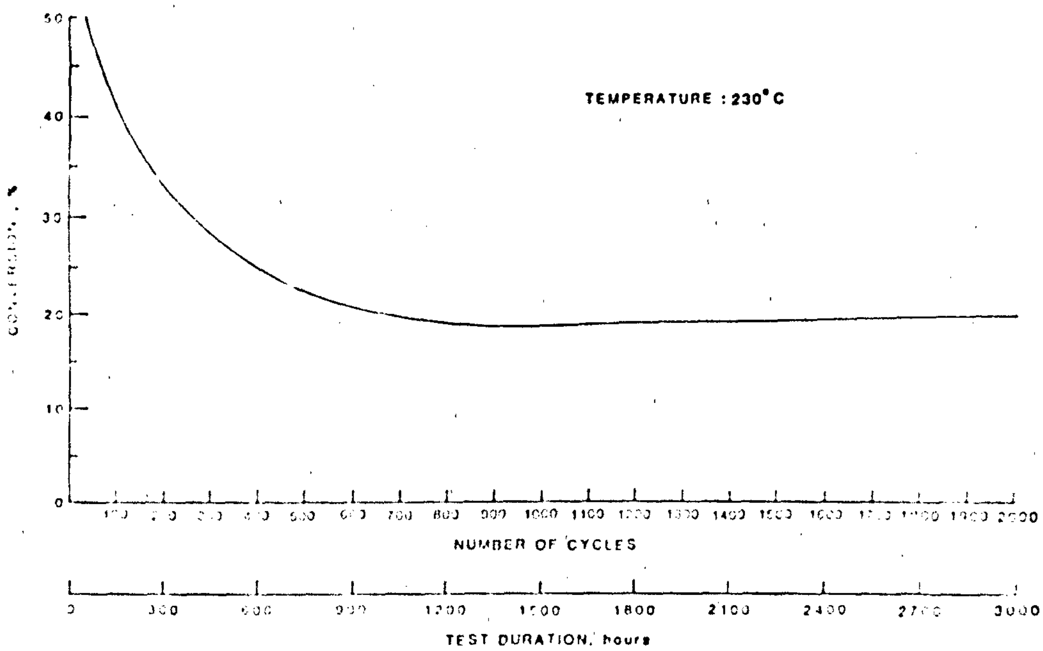
9,750 hr^{-1} (product hydrogen, standard conditions) to obtain about 50% initial conversion of methanol. As seen in Figure 6.7, the bed performance stabilized after the expected initial drop in activity. These results demonstrate the thermal cycling capability of the reformer catalyst for the required 2000 cycles.

For the brassboard and prototype power plants, catalyst beds filled with 1/8 in. pellets of United Catalyst T-2107 catalyst were employed. This catalyst is essentially identical to T-2130 which has been discontinued by the supplier. Pelletized catalyst was selected over the stratified or crushed catalyst beds to eliminate the particulate entrainment problem faced with the later two designs. Uneven flow distribution in the catalyst bed caused hot spots. This was corrected by installing a perforated baffle plate below the catalyst bed support screen and introducing the reformate gas tangentially in the catalyst bed.

6.2.4 Other Fuel System Components

Several commercial components were modified to better adapt them to the service requirements of the methanol power plant. The solenoid operated valves required addition of heat sinks and change in diaphram material from Viton to Silicone rubber. The transfer pump wetted parts were nickel plated.

A surge damper tank with a volume of about 50 ml installed upstream of the fuel injector was found to effectively dampen fuel line pressure fluctuations.



CATALYST THERMAL CYCLE TEST

FIGURE 6.7

STABILITY OF UNITED CATALYST'S CATALYST T-2130

SD0210R

THIS PAGE INTENTIONALLY LEFT BLANK

7.0 NEAT METHANOL SYSTEM

A 3kW breadboard power plant operating on neat (undiluted) methanol was developed and tested. The power plant design incorporates the recovery of water from the power plant exhaust streams, mixing with methanol, and steam reforming of the mixed fuel.

7.1 WATER RECLAIM ANALYSIS

Water recovery was studied by ERC under a previous U.S. Army contract [2]. It was concluded that with a direct air-cooled fuel cell stack, water recovery was not a practical option. Subsequent changes in stack design [3,4], introduced during the late seventies and early eighties, permitted separation of cooling air from cathode air and operation with 1.5 to 2 times stoichiometric cathode air. This provides a cathode gas exit stream with high concentration of water, and makes water recoverable by using an ambient air-cooled condenser.

The combined cathode exhaust gas and reformer flue gas streams of a fuel cell power plant operating on a 1:1.3 molar mixture of methanol-water fuel carry 3.3 moles of water for each mole of methanol consumed. Only 39% of the water needs to be recovered to meet the reformer water requirement.

The distribution of water between the cathode exhaust and the reformer flue streams depends mainly on the stoichiometric air rate supplied to the stack and burner, and upon hydrogen utilization in the stack. For typical hydrogen and air stoichiometric rates, the water content of each of the streams is greater than required for the reformer. However, recovery of sufficient water from any single stream at hot ambient conditions would require the use of a chiller, which is unacceptable for small plants.

Significant water recovery can be achieved with the system shown in Figure 7.1 where water is recovered from the cathode exhaust and reformer flue streams. The water recovery potential

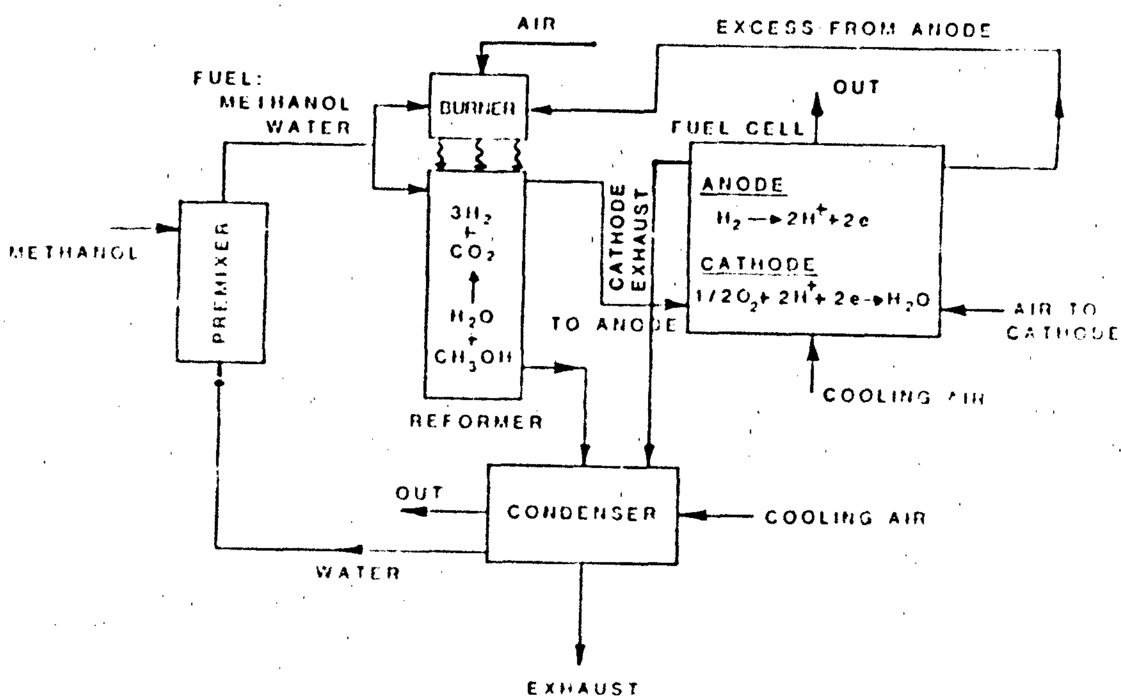


FIGURE 7.1

NEAT METHANOL POWER PLANT CONCEPT
(Water Recovery From Reformer and Cathode Exhuasts)

SD0025C

of this scheme is mapped in Figure 7.2. These data indicate that operating on 55-60% air and 50-65% fuel utilization, with an approach temperature of 8-10°C (15-20°F) in an air-cooled heat exchanger, adequate water may be recovered at ambient temperatures as high as 43°C (110°F). At higher ambient temperatures (125°F), water must be recovered from the combustion products of the anode and cathode streams as shown in Figure 7.3. The operating boundaries for water recovery of this approach are given in Figure 7.4.

7.2 POWER PLANT DESIGN

Based on the premixed fuel power plant design and test results of a water reclamation study, a neat methanol power plant was designed.

A functional schematic diagram of the power plant showing the key components is given in Figure 7.5. A photograph of the brassboard power plant constructed and delivered to the U.S. Army is shown in Figure 7.6.

Power plant operation, incuding startup and shutdown, was automatic. External power supplies were used for powering electrical components during startup. Control elements, driver circuits, sensors, and the controller are identical to the 3/5kW premixed methanol power plant.

The reformer design was based on the 3/5kW reformer. The main modifications were increased combustion chamber volume and improved flue gas leak-tightness.

The 80-cell separated air-cooled phosphoric acid fuel cell stack used in this power plant was similar to the stacks used in the 3kW mixed fuel power plant.

A 45 cm x 36 cm x 5 cm (0.3 ft^3) automotive type air-cooled (cross-flow) copper heat exchanger (Figure 7.7) was used for water reclamation. A 48V, 0.5A brushless DC blower was used to

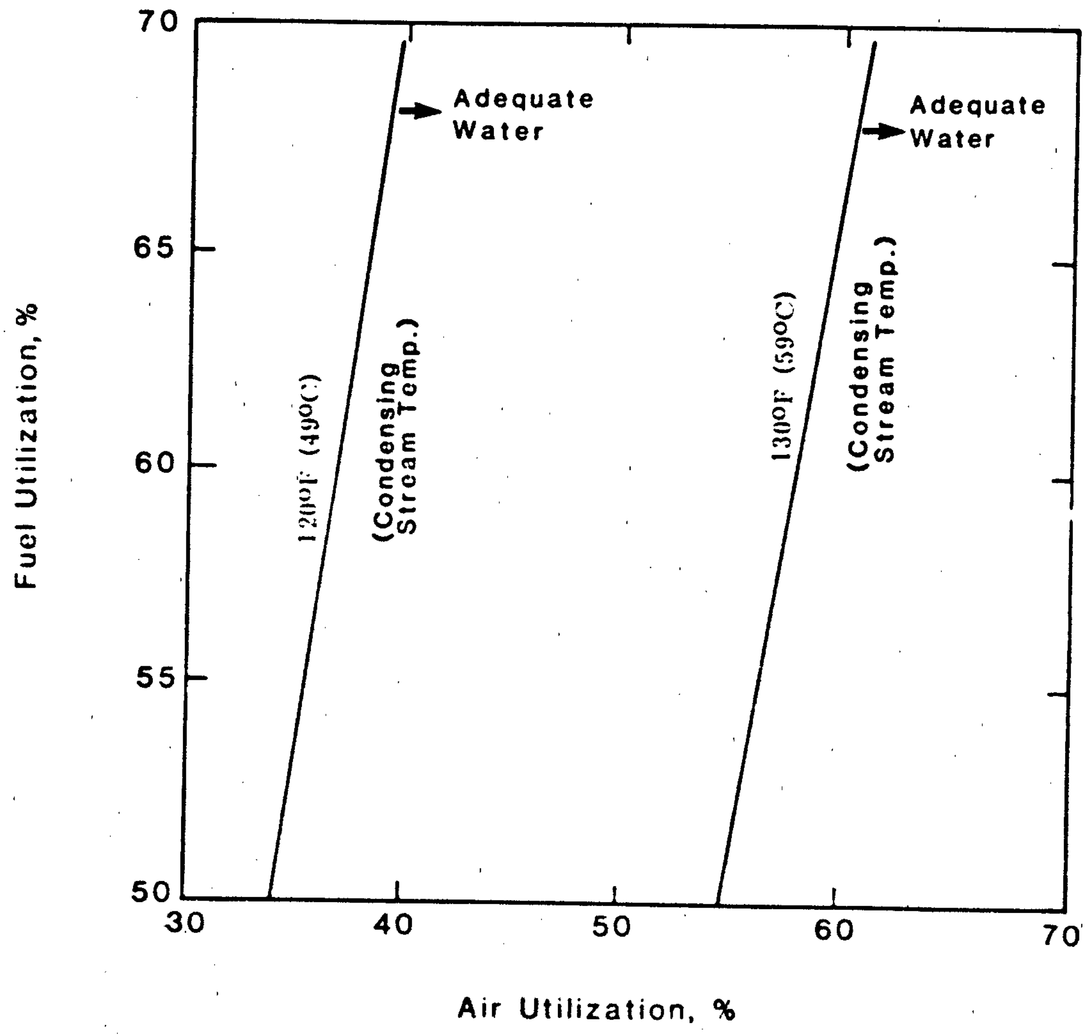


FIGURE 7.2

OPERATING PARAMETER RANGE FOR WATER RECOVERY
(Water Recovery From Reformer and Cathode Exhausts;
50% Excess Air for Burner)

SD0287

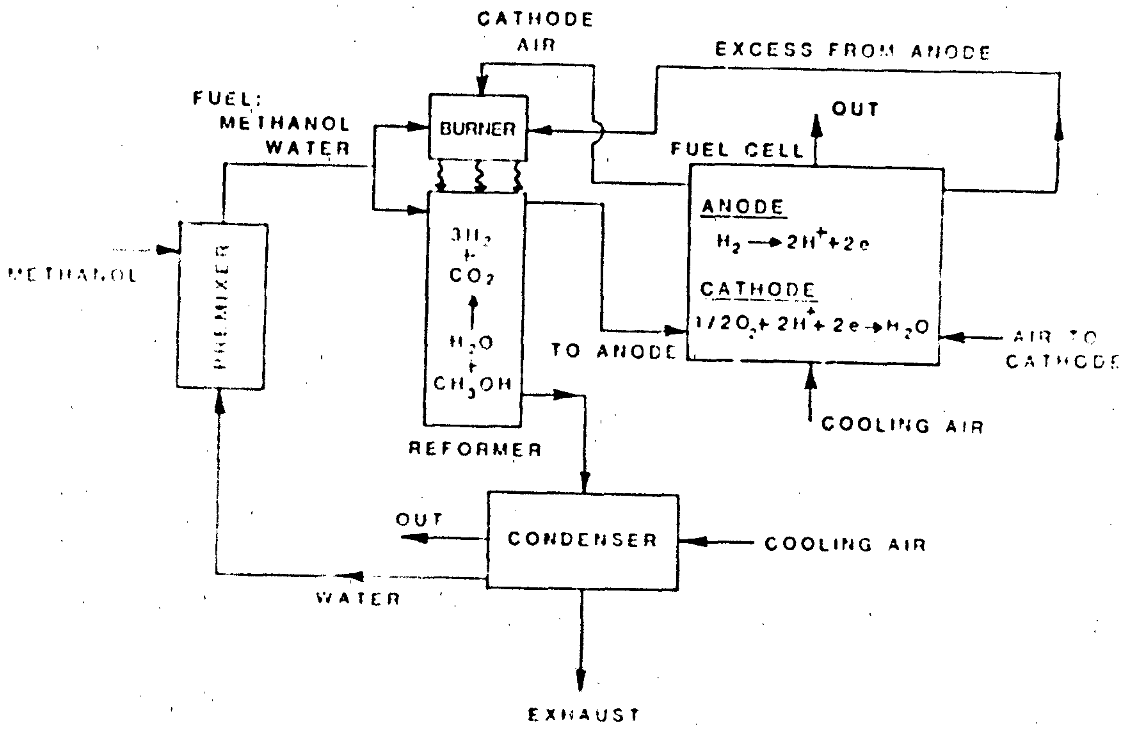


FIGURE 7.3

NEAT METHANOL POWER PLANT
(Water Recovery From Anod- Cathode Combustion Products)

SD0025

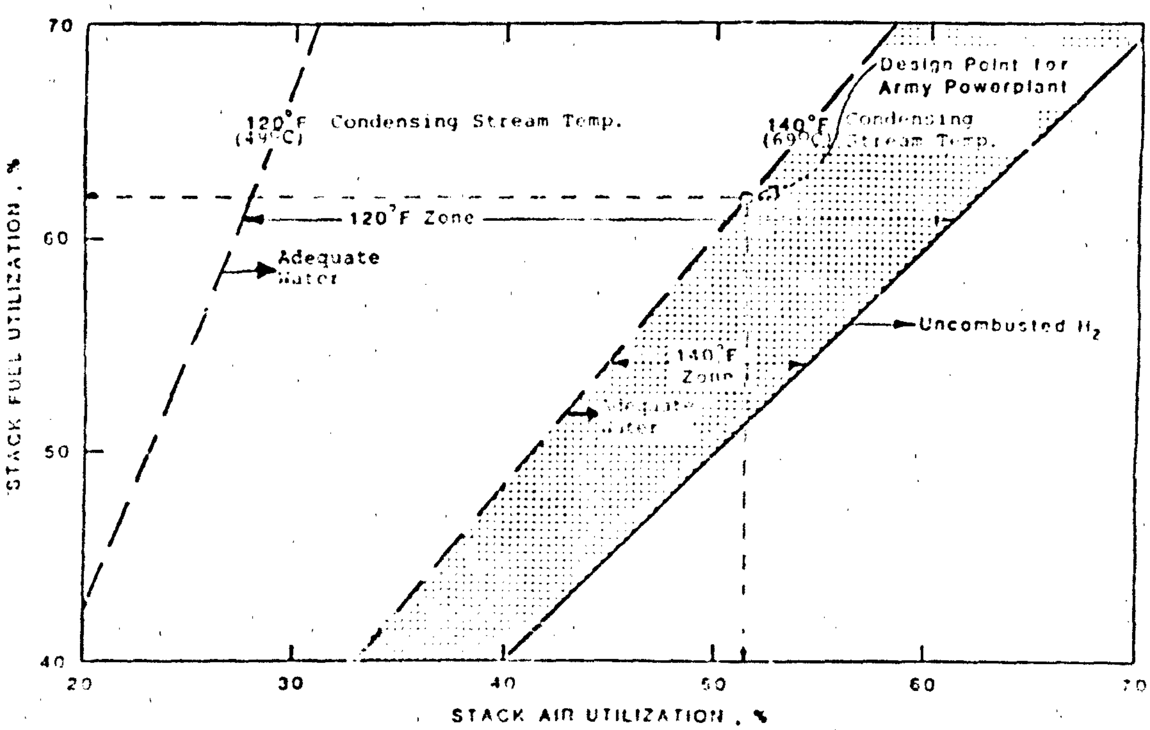


FIGURE 7.4

OPERATING PARAMETERS FROM WATER RECOVERY
(From Combustion Products of Anode and Cathode Streams)

SD0093R

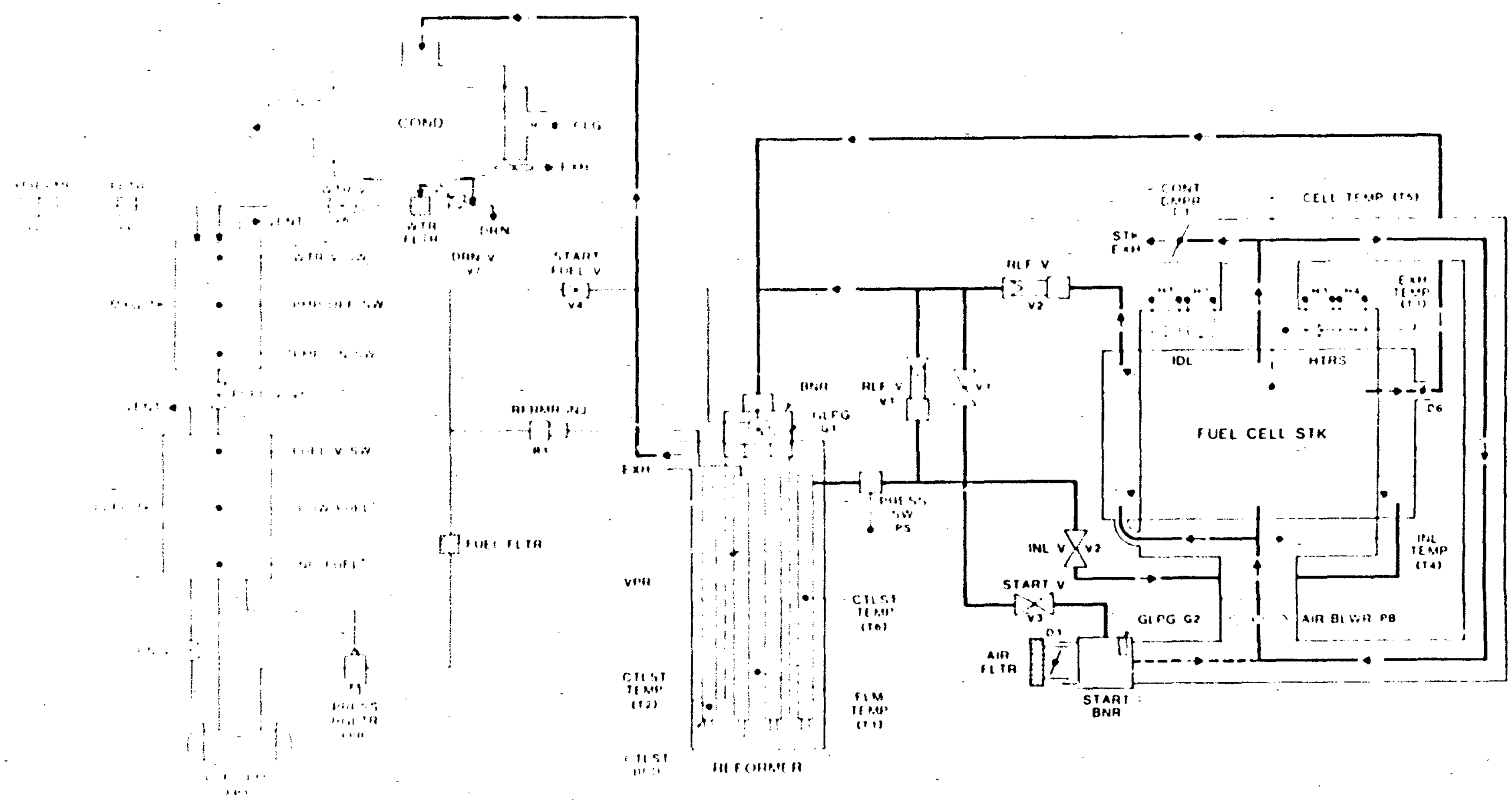


FIGURE 7.5
KEY COMPONENTS OF THE ARMY 3kW NEAT METHANOL POWER PLANT

SD0241

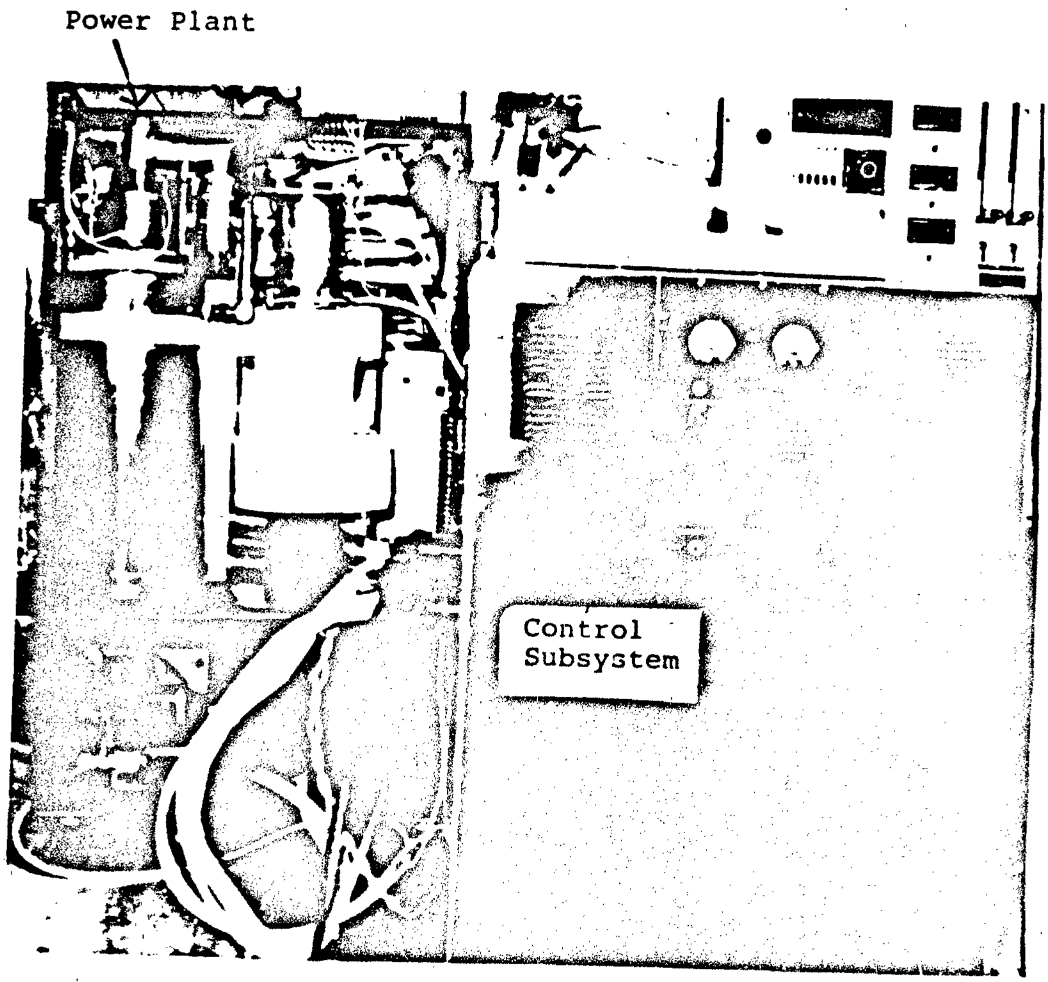


FIGURE 7.6
A PHOTOGRAPH OF THE BRASSBOARD POWER PLANT

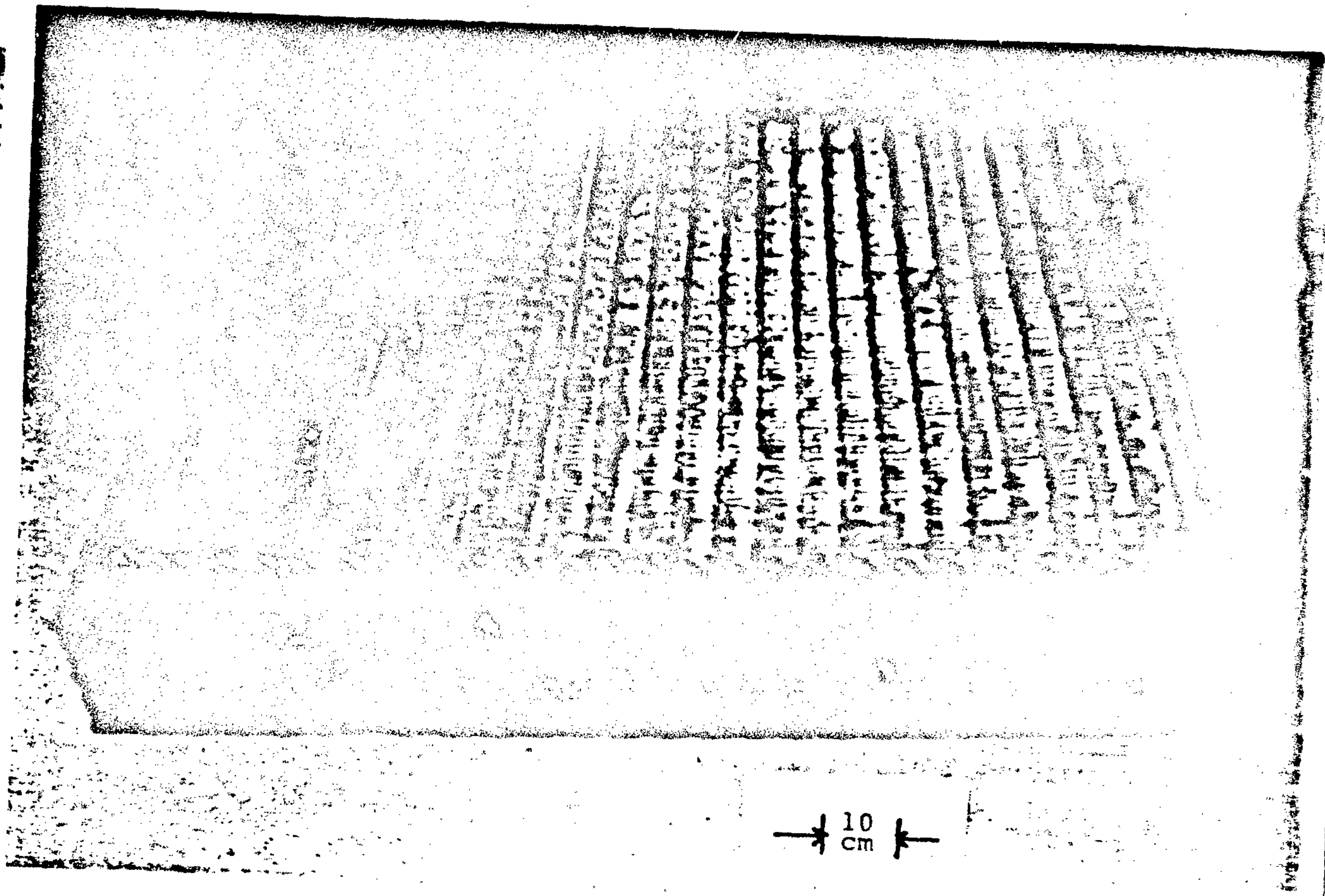


FIGURE 7.7 A PHOTOGRAPH OF THE WATER RECLAIM BRASSBOARD POWER PLANT CONDENSER

provide condenser cooling air. This fan was powered directly from the stack during operation and from the 24V bus during the startup. When operating on 24V, the fan provides about 60% of the air available at the rated 48V operation.

A fully automatic onboard water reclamation and fuel mixing device incorporating a gravity mixing concept was designed (Figure 7.8). Methanol is first pumped from the external supply into the mixing tank to a desired level. Water from the condenser then flows into the tank. When this tank is full, the fuel is transferred from the mixing tank to the fuel tank. During shutdown, the drain valve drains water stored in the system eliminating any freezing problems. The system operates automatically using float switches and magnetic relays.

7.3 TEST RESULTS

The brassboard neat methanol power plant was tested at various levels from idel to full load as shown in Figure 7.1. The important observations from this testing are:

1. About 100% excess water was collected at all loads with 27°C room temperature. An approach temperature of about 11°C (19°F) between the ambient air and the condenser hot gas side exhaust temperature was projected for full load operation.

2. Power plant efficiency was roughly equal to the premixed fuel power plant efficiency. For a gross power output of 4kW, neat methanol consumption was about 2.13 kg/hr.

3. Steady state power plant operation at various loads with automatic mixing of fuel (58 wt% methanol and 42 wt% water) and the delivery of the fuel to the reformer.

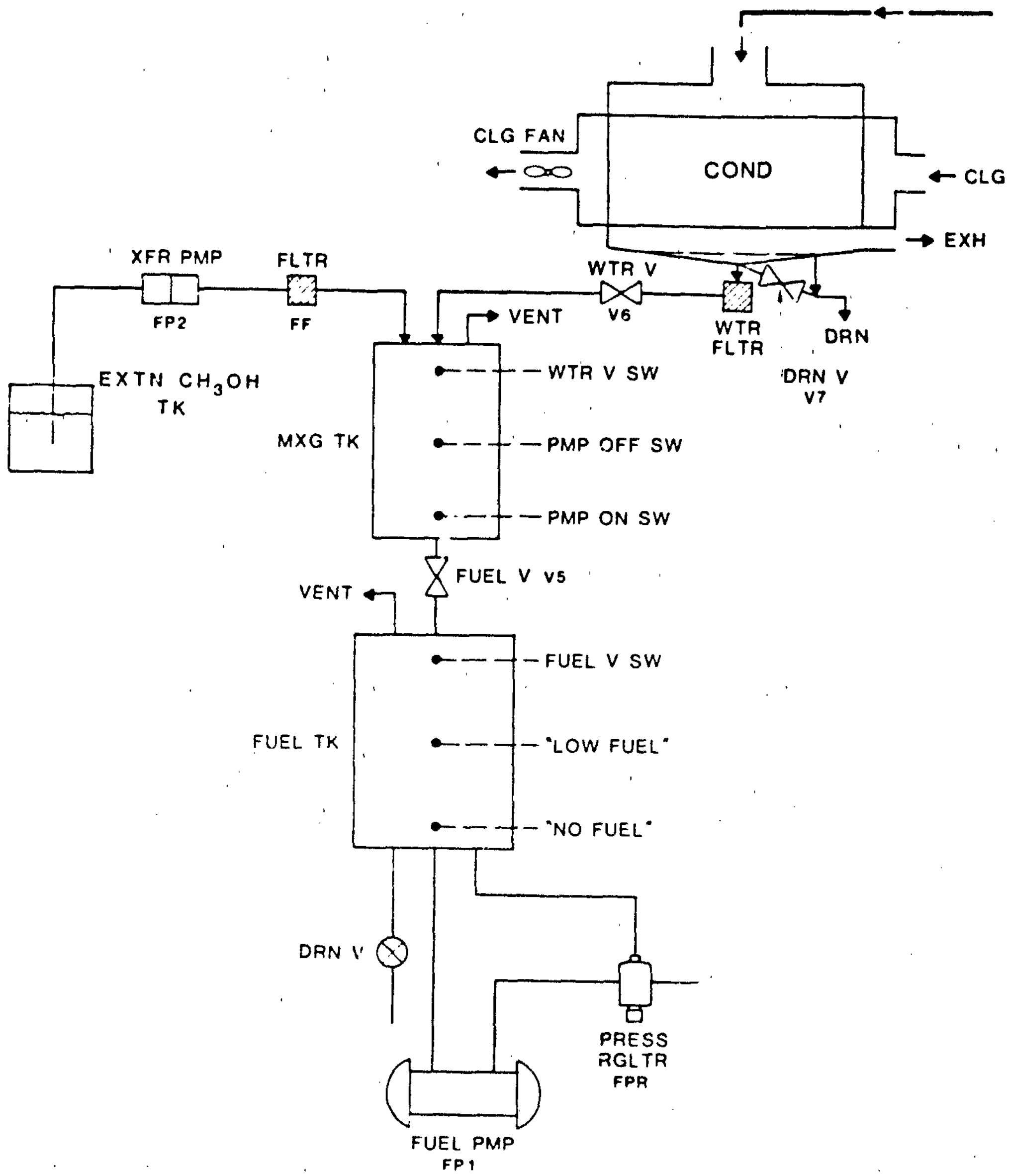


FIGURE 7.8
WATER RECLAMATION AND FUEL PREPARATION SYSTEM

SD0243a

TABLE 7.1

BRASSBOARD NEAT METHANOL POWER PLANT PERFORMANCE

OBSERVED				
Stack Current, A	48.3	62.3	74.5	84.6
Gross Stack Power, W	2,450	3,144	3,860	4,019
CH_3OH Consumption, Kg/hr	1.34	1.65	2.02	2.18
Mixed Stream Inlet Temperature, ^oC	148	162	185	187
Condenser Heat Load, KW-hr	1.73	2.37	2.81	3.00
Condenser Approach Temperature*, ^oC	8.22	11.4	18.1	18.4
Water Reclaimed, Kg/hr	1.74	2.20	2.74	2.91
PROJECTED (FOR NECESSARY WATER RECLAMATION CASE)				
Water Reclamation Required, Kg/hr	0.97	1.20	1.46	1.58
Condenser Heat Load, KW-hr	1.54	1.64	1.93	2.03
Approach Temperature, ^oC	3.06	6.11	9.72	10.6

* Condenser cooling air flow rate: 227 gm-moles/min.

4. The load following capability of the neat methanol system was similar to that of the premixed system.

5. Total weight of the water reclamation related hardware is less than 25 lbs.

This testing demonstrated that a simple neat methanol fuel cell power plant based on water reclamation is a practical option for the SLEEPS application.

THIS PAGE INTENTIONALLY LEFT BLANK

8.0 CONCLUSIONS

The efforts of this program have resulted in the development of the phosphoric acid fuel cell power source for transportable power generation applications. The fuel cell power plant source possesses some unique features such as:

- quiet operation
- high efficiency
- operable at extreme temperatures
- uses non-petroleum fuel

The power plant is potentially reliable, because, the design incorporates low temperature operation and minimal number of moving parts. Operation of the power plant on both methanol-water premix and neat methanol fuels has been demonstrated.

Improvement of performance and reduction in weight and volume of the power plant can be achieved through reducing stack size (improved cooler design and cathode catalyst) repackaging electrical system components, using a brushless DC stack fan and eliminating some valves and dampers. Power plant endurance tests should be performed to identify the components affecting reliability and maintainability and improve the design. Also, value engineering efforts need to be pursued to reduce the cost of a unit.

REFERENCE

1. S. Abens, M. Farooque and R. Jacobs, Extended Abstracts, 164th ECS Meeting, Volume 83-2, Paper No. 375, Washington, DC, October, 1983.

2. S. Abens et al, Final Technical Report, U.S. Army MERADCOM Contract No. DAAG53-79-C-0118, April, 1978.

3. R.E. Kothmann, U.S. Patent No. 4,276,355 (June 30, 1981).

4. D.Q. Hoover Jr., Final Report, DOE/NASA Contract No. DEN3-161, (NASA CR - 165193), February 1982.

APPENDIX A

APPENDIX A
COMPONENT DESCRIPTION
(3.0 kW AC/DC Models MEP 051A/MPE 050A)

SUBSYSTEM	COMPONENT(S)	SOURCE DATA		FUNCTION
		VENDOR	MODEL/DWG #	
Frame and Structural Subsystem	Structural Assembly	ERC	DWG# 84785000	Supports power plant components.
	Skin Material	Prolam Inc.	FR4 0-1-0	Protects the unit from rain, snow and dust.
	Shock Absorbers	Lord Kinematics	J-5425-203	Reduces shock and vibration.
	Air Filters	ERC	103-1, 103-2, 103-3	Filters intake air.
Fuel Cell Stack Subsystem				
	Fuel Cell Stack Assembly	ERC	DWG# 84005010	Unregulated DC power source.
	Control Valve Assembly (D3)	ERC	DWG# 83185033	Operated by a power amplifier Servo. Provides stack temperature control.
	Sealing Damper Valve Assemblies (D1, D2 and D6)	ERC	DWG# 83185033	Operated by On/Off transistor switch. Provides hermetic seal for stack.
	Damper Motor (4)	TRW	43A150-3	Used in a valve assembly to drive damper.
	Blower (PB)	IMC Magnetics	BC3825B-11	Stack cooling air blower. Runs on 115 VAC 400 Hz.
	R'D (T3,T4 and T5)	Omega Engineering	PR-11-2-100-1/8-6-1/2E	Stack temperature sensing.

SUBSYSTEM	COMPONENT(S)	SOURCE DATA: VENDOR	SOURCE DATA: MODEL/DWG #	FUNCTION
Fuel Cell Stack Subsystem cont'd.	Insulation	IMI-Tech	Solimide 1/2"	Fuel Cell Stack Insulation
	Idle Heater Pack (H1,H2,H3 and H4)	ERC	203	Maintains minimum stack current 6.5 Ω each.
Fuel Conditioning Subsystem	Reformer Assembly	ERC	DWG# 84005001	Converts methanol-water fuel to hydrogen-rich gas.
	Burner Blower (BB)	Rotron	Aximax-2 1371YF # 010091	Provides combustion air. Speed control by a variable voltage and variable frequency supply.
	Glow Plugs (G1 & G2)	Hupp	HV-1-54733	Provides Ignition
	Nozzle	Hago	1.35 gal/hr, 80°	Used for liquid fuel combustion.
	Thermocouple (T1)	Omega Engineering	TJ36-CAIN-116U-24 Iach	Senses burner flame temperature.
	RTD (T2 & T6)	Omega Engineering	RR-11-100-1/8-18-1/2-E	Senses fuel temperature and catalyst bed temperature.
	Fuel Filter	Hago	AOM	Filters liquid fuel.
	Start Fuel Valve (BV)	Brunswick Technetics	A2014, 24 VDC	Solenoid operated On-Off valve for fuel burner during startup.
	High Pressure Pump (FPI)	Tuthill Pump Co.	B9767MCW	Provides fuel system pressure.

SUBSYSTEM	COMPONENT(S)	SOURCE DATA		FUNCTION
		VENDOR	MODEL/DWG#	
Fuel Conditioning Subsystem cont'd.	Low Pressure Pump (FP2)	Facet Enterprises	48C521	Pumps fuel from external supply to internal tank. Float swtich controlled operation.
	Fuel Pressure Regulator (FPR)	Cash-Acme	1535361 (40-90 psi)	Regulates delivery pressure of liquid fuel.
	Reformer Injector (RI)	General Motors	2753K6	Provides controlled fuel flow to the reformer.
	Pressure Relief Valve (PRV)	Circle Seal Controls	A-559A-6M-0-0.5FF	Protects fuel cell stack and reformer from overpressure.
	Pressure Switch (PS)	CCC	211C50	Causes power plant shutdown in case of overpressure.
	Fuse-Link	Micro Devices	4300	Ensures a safe shutdown if burner blower malfunctions.
	Insulation	Contronics	370-4	Reformer assembly insulation.
	Day-Tank Assembly	ERC	DWG# 83035001	Holds 15 minute fuel supply. Float switch controlled operation.
	Level Switch	Delaval GMS Sensors	L5800-43568	Supplies signal to micro-processor to operate the transfer pump.
	Drain Valve	Nupro	554JB	Draining of the internal reservoir during maintenance.

SUBSYSTEM	COMPONENT(S)	SOURCE DATA VENDOR	SOURCE DATA MODEL/DWG #	FUNCTION
Fuel Conditioning Subsystem cont'd	Vent	Ford	D1TZ-9B593-C	Ensures atmospheric pressure operation of the internal fuel reservoir.
	Gas Valves (V1,V2,V3, and V4)	Skinner-ERC Modified	DWG# 81035179	Directs gas flow path and provides sealing. Solenoid operated.
Control Subsystem	Computer Assembly	CCC	3MC1	Controls power plant operation. Uses an Intel 8051 series CPU having 8k Bytes of memory.
	Control Panel	CCC	5MC1	On-Off control and monitoring.
	Power Driver Assembly	CCC	7MC1	Interfaces between microprocessor and auxiliary components.
Electrical Subsystem	Relay Assembly	ERC	383	Controls on-off power to ancillary components.
	Battery Assembly	ERC	583	Provides power for startup and shutdown. Uses 20 Eagle-Picher, EPI-18137 cells.
	Charger Assembly	ERC	483	Constant current temperature compensated charging of the battery.
	400 Hz Inverter	Avionics	1B800-1A	Inverts 24 VDC to 115 VAC, 400 Hz for stack air blower.

SUBSYSTEM	COMPONENT(S)	SOURCE DATA VENDOR	SOURCE DATA MODEL/DWG #	FUNCTION
Electrical Subsystem cont'd.	Housekeeping Power Supply	Bikor	DCX561	Provides regulated DC voltages from battery or fuel cell stack output.
	Muffin Fan	Pamotor	4124X	Provides cooling air for housekeeping supplies and power driver box.
	Heater Relays (4)	Durakool	AFM20-310M	Controls power to idle heaters.
	Diodes (2)	Motorola	1NM86A	Prevents reverse voltage to power supplies.
	Fuses (2)	Buss	KAH60	Prevents short circuit damage.
	Meter Shunt	Ampro	MSA 151 (50 mV/150A)	Provides analogy input to microprocessor.
	Power Relays (2)	Cutler-Hammer	MS2414.-D1	Switching devices for power supplies.
	Power Relay	Cutler-Hammer	MS24182-D1	Main load contactor.
	Limiter	Buss	ANN150	Over current protection for DC power conditioner.
	Auxiliary Power Connector	Electro-Tech. Inc.	11674728	Connection for auxiliary 24V source.
	Ground Terminal	Dossert	DGN2F-S-RPC	Unit earth grounding post.
	AC Power Conditioner	GFE	EMIR 302	Inverts FC stack output to controlled AC.
	DC Power Conditioner	Bikor	DCX 560	Converts FC stack output to regulated DC.

APPENDIX B

APPENDIX B

LISTING OF MICROPROCESSOR INPUT/OUTPUT CHANNELS

DIGITAL OUTPUTS

Mnemonic	Description
CD1	16 Position Control Damper
CD2	16 Position Control Damper
CD3	16 Position Control Damper
CD4	16 Position Control Damper
G1	Reformer Glow Plug
P1	High Pressure Fuel Pump
G2	Startup Burner Glow Plug
P2	Transfer Pump
B2	Burner Blower Speed Control
B2	Burner Blower Speed Control
B3	Burner Blower Speed Control
B4	Burner Blower Speed Control
B5	Burner Blower Speed Control
B6	Burner Blower Speed Control
EWL	Wait Lamp
ERL	Ready Lamp
ESL	Standby Lamp
ECL	Charging Lamp
RI	Reformer Injector
PB	Process Air Blower
H1	Idle Heater (8 Amps)
H2	Idle Heater (8 Amps)
H3	Idle Heater (8 Amps)
H4	Idle Heater (8 Amps)
V1	Bypass Fuel Valve
V2	Stack Fuel Valve
V3	Startup Burner Valve
BV	Reformer Burner Valve
K1	Output Relay

DIGITAL OUTPUTS cont'd.

Mnemonic	Description
K2	Battery Relay
K3	Parasitic Relay
D1	Sealing Damper
D2	Sealing Damper
D6	Sealing Damper
WD	Watchdog Control Circuit

DIGITAL INPUTS

Mnemonic	Description
IST	Start Switch
ILF	Low Fuel Switch
INF	No Fuel Switch
IOF	Off Switch
IPR	Pressure Switch

ANALOG INPUTS

CHANNEL	MNEMONIC	DESCRITION	FULL SCALE	ACCURACY
1	T1	"K" TC FLAME DETECT	2047°F	20°F
2	T2	RTD SUPERHEAT TEMP	1100°F	10°F
3	T3	RTD EXHAUST TEMP	511°F	5°F
4	T4	RTD INLET & FLAME TEMP	1023°F	10°F
5	T5	RTD CELL TEMP	511°F	5°F
6	T6	RTD CATALYST TEMP	511°F	5°F
7	VS	STACK VOLTAGE	64V	0.25V
8	LS	STACK LOAD SHUNT	42.3mV/127A	.33mV/1A

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C

APPENDIX C.

PERTINENT CONVERSION FACTORS/PROPERTIES/EQUATIONS/DEFINITIONS

CONVERSIONS

1 lb	=	454 gms
1 Btu	=	252 cal
	=	0.2929 W-hr
1 foot	=	0.3048 meter
T, °F	=	1.8 x T, °C + 32
1 US gal (liq.)	=	3.785 liter

PROPERTIES

Methanol (CH_3OH)

Molecular Weight	=	32.04
Weight per US gallon at 68°F	=	6.59 lbs
Boiling point at 760 mm Hg	=	64.7°C
Freezing point	=	-97.8°C
Heat of combustion at 25°C 760 mm Hg		
HHV	=	9777 Btu/lb
LHV	=	8596 Btu/lb

Hydrogen

Molecular Weight	=	2.016
Heat of combustion at 25°C 760 mm Hg		
HHV	=	61,051 Btu/lb
LHV	=	51,605 Btu/lb

MASS BALANCE EQUATIONS

Basis: 1 mole of CH_3OH

Reformer

IN: $CH_3OH + 1.3\ H_2O$

OUT: $3H_2 + CO_2 + 0.3\ H_2O$

MASS BALANCE EQUATIONS cont'd

Fuel Cell

IN: $(3H_2 + CO_2 + 0.3\ H_2O)_{Anode} + (yO_2 + 3.8y\ N_2)_{Cathode}$

OUT: $[(3-x)H_2 + CO_2 + z\ H_2O]_{Anode}\ \ [(y-\frac{x}{2})O_2 + (x + 0.3-z)H_2O]$

where, x = moles of hydrogen consumed by the electrochemical reaction.

y = moles of oxygen entering the fuel cell.

z = moles of water exiting from fuel cell with the anode stream.

Reformer Burner

IN: $[(3-x)H_2 + CO_2 + z\ H_2O]_{Fuel} + [m\ O_2 + 3.8r\ N_2]_{Air}$

OUT: $(3-x)H_2O + CO_2 + (3-x+z)H_2O + (m - \frac{3-x}{2})O_2 + 3.8\ m\ N_2$

where, m = moles of oxygen entering the burner.

DEFINITIONS/EQUATIONS

a. Stack Fuel Utilization; %: $\frac{x}{3} \times 100$

b. Stack Air Utilization; %: $\frac{x}{2} \times \frac{100}{y}$

c. Reformer Burner Air Utilization; %: $\frac{(3-x)}{2} \times \frac{100}{m}$

d. Hydrogen flow to fuel cell, scfm:

(MeOH Flow, lb-moles/min) X 3 $\frac{\text{moles of } H_2}{\text{mole of MeOH}}$ X 379 ft^3/lb-mole

e. Power Plant Efficiency; %:

$$\frac{\text{Net Output Power, Watts}}{\text{LHV of Methanol Consumed}} \bigg| 100$$

$$= \frac{\text{Net Output Power, Watts X 100}}{(\frac{\text{lb fuel,mix}}{\text{hr}})[.5776\ \frac{\text{lb MeOH}}{\text{lb fuel,mix}} \times \frac{\text{8596 Btu}}{\text{lb MeOH}} \times \frac{\text{.29407 Watt}}{\text{Btu/hr}}]}$$

DEFINITIONS/EQUATIONS cont'd.

f. Hourly Space Velocity

Basis: Volume of total dry gas at the reactor outlet at STP ($60^{o}F$, atm) per volume of catalyst.

$$HSV = \frac{\left(\frac{\text{lb fuel,mix}}{\text{hr}}\right) \times 0.5776 \frac{\text{lb MeOH}}{\text{lb fuel,mix}} \times \frac{\text{1 lb-mole MeOH}}{\text{32 lb MeOH}} \times \frac{\text{4 lb-moles of gas}}{\text{lb-mole MeOH}} \times \frac{379\ \text{ft}^3}{\text{lb-mole}}}{\text{Catalyst Volume, ft}^3}$$

DISTRIBUTION LIST

Defense Technical
  Information Center (12)
Cameron Station
Alexandria, VA 22304-6145

Chief (1)
Research Development & Acquisition
  Office, Deputy Chief of Staff
Department of The Army
Washington, DC 20310

Office of The Under Dep Sec (1)
  of Defense (Res & Adv Technology)
ATTN: ASST DIR, Electronics &
  Physical Sciences
Washington, DC 20301

Director, Tech Information (1)
Advanced Res Proj Agency
1400 Wilson Blvd
Arlington, VA 22209

Commander (1)
US Army Materiel Development
  and Readiness Command
5001 Eisenhower Avenue
Alexandria, VA 22333

Electric Power Research Inst (1)
ATTN: A. P. Fickett
P. O. Box 10412
Palo Alto, CA 94304

Logistics Evaluation Agency (1)
ATTN: DALO-LEI (Jack Daveau)
New Cumberland Army Depot
New Cumberland, PA 17070

Commander (1)
US Army Training & Doctrine Command
ATTN: ATCD-MC (MAJ Miller)
Fort Monroe, VA 23651

Power Information Center (1)
Franklin Research Center
20th and Race Streets
Philadelphia, VA 19130

Engelhard Industries Div (1)
Engelhard Minerals & Chem Corp
ATTN: V. A. Forlenza
Menlo Park, Edison, NJ 08817

International Fuel Cells(1)
ATTN: Mr. Al Meyer
P. O. Box 109
Governor's Highway
South Windsor, CT 06074

Technical Documents Center (2)
Belvoir Research & Development
  Center
ATTN: STRBE-TB
Fort Belvoir, VA 22060-5606

DoD Proj Mgr-Mobile Elec Pwr (1)
ATTN: DRCPM-MEP-TM (J. Wasdi)
7500 Backlick Road
Springfield, VA 22150